# *STANDARDS FOR DYNAMICS IN FUTURE ELECTRIC ENERGY SYSTEMS*

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# Outline

- Four basic functionalities of standards for electric energy systems
- Examples of problems related to lack of standards for dynamics in today's industry
- Summary of standardization efforts for smart grids
- Three possible approaches to standardization for dynamics
- Illustrations using small examples

# Four basic functionalities of standards for electric energy systems



- Standards must ensure **safety of components**; safety of interactions among group of components; and safety of interactions of the system as a whole.

- Standards must ensure that **the electric energy system continues to function as an interconnected AC system**; further considerations are required to ensure that hybrid AC/DC interconnected systems are compatible and continue to function as a single interconnected system. System standards for interconnecting micro-grids, ranging from AC to all DC, to the bulk AC power system must be such that the hybrid AC/DC/AC system remains in synchronism.

# Four basic functionalities of standards for electric energy systems (cont.)

- Standards must **meet quality-of-service (QoS) as defined by the (groups of) system users**; in particular, sustained variations in frequency and voltage deviations seen by the system users (both producers and consumers) away from nominal must be maintained within the thresholds specified by the standards.
- Dynamic standards must play **the role of a powerful catalyst for integrating unconventional resources, demand response, and grid control technologies**. Depending on the principles of their design, they could be **standards and/or flexible, interactive, self-adapting protocols**.

# Issues with standards for ensuring safety

- Well-understood functionality for components
- Component-level specifications of acceptable operating limits (generation, T&D, customers)
- Protection embedded virtually into every single component
- Peculiar safety challenges at the system level

  -**harmonic resonance problem** (transformer destroyed by the resonance of specific harmonic) [1,2]

  **-sub-synchronous resonance (SSR) between turbine shafts and series capacitor banks (long transmission lines)** [3]

# Safety problems caused by harmonic resonance [1,2]

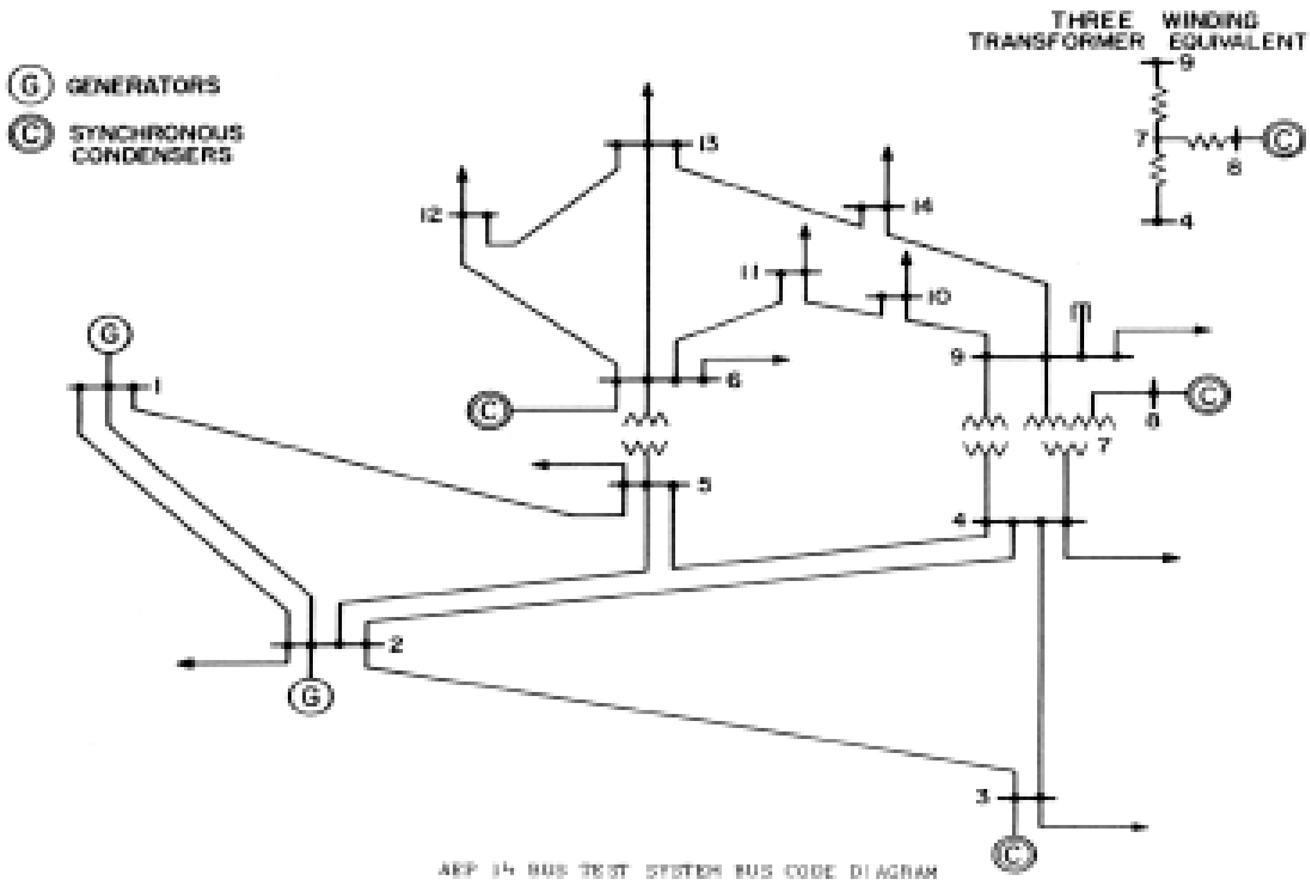



Fig. 1. IEEE 14- bus system.

# Nonlinear load connected to bus no3.

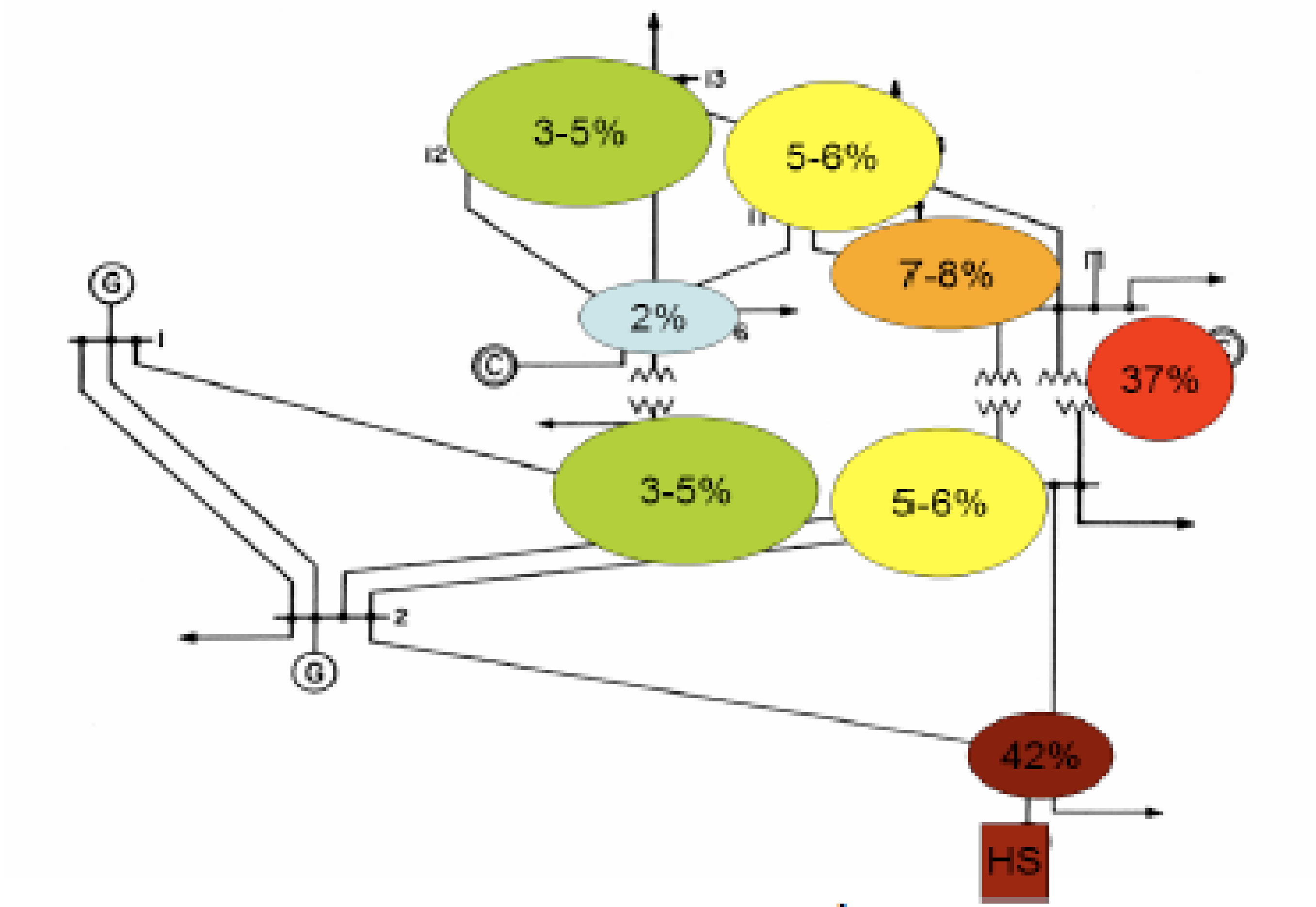



Fig. 3. Harmonic propagation for 5th harmonic in Case I.

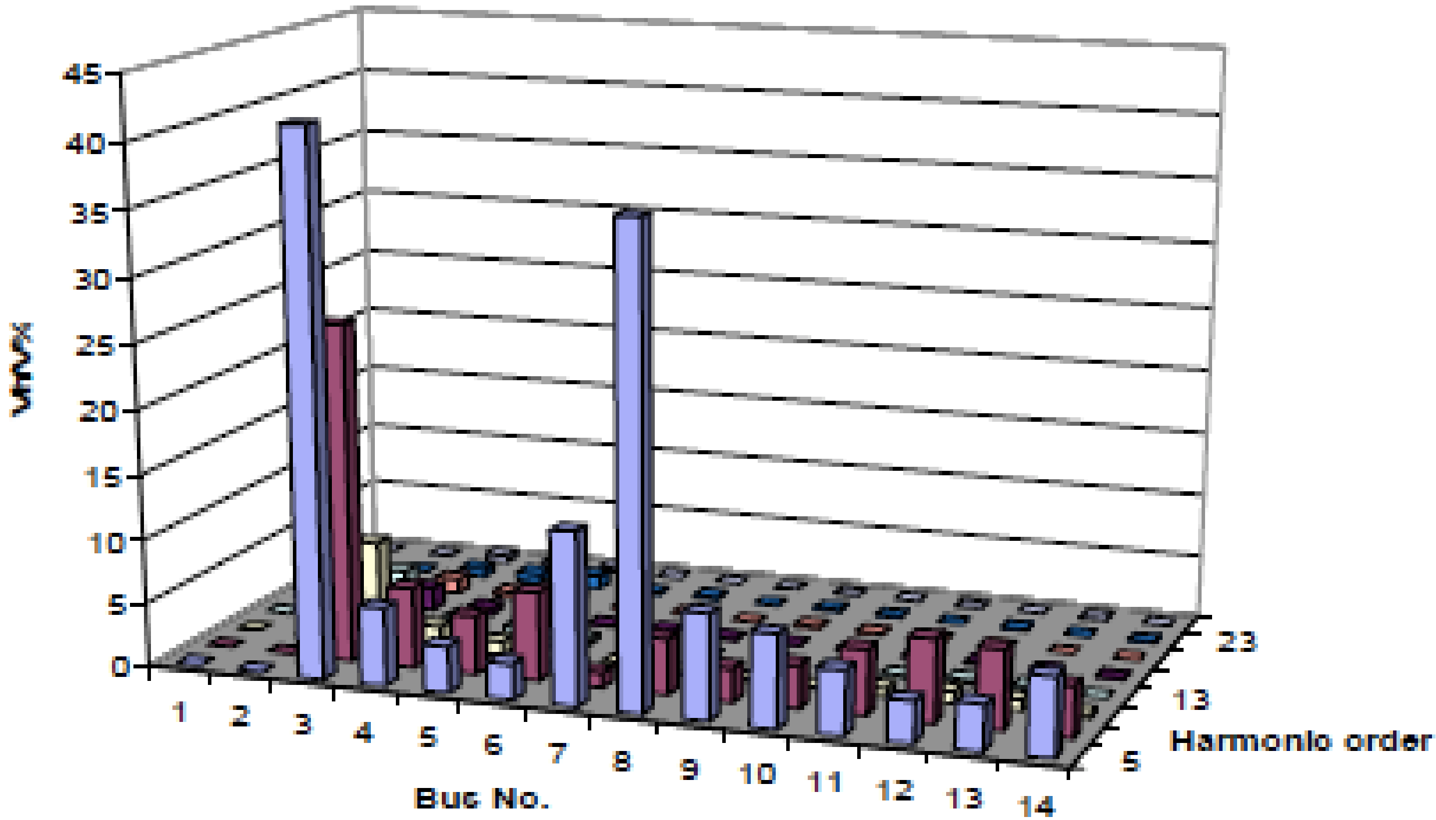



Fig. 2. The percentage of harmonic voltage to normal at different harmonics order when the harmonic source connected at bus 3.

# Harmonic source at bus 6

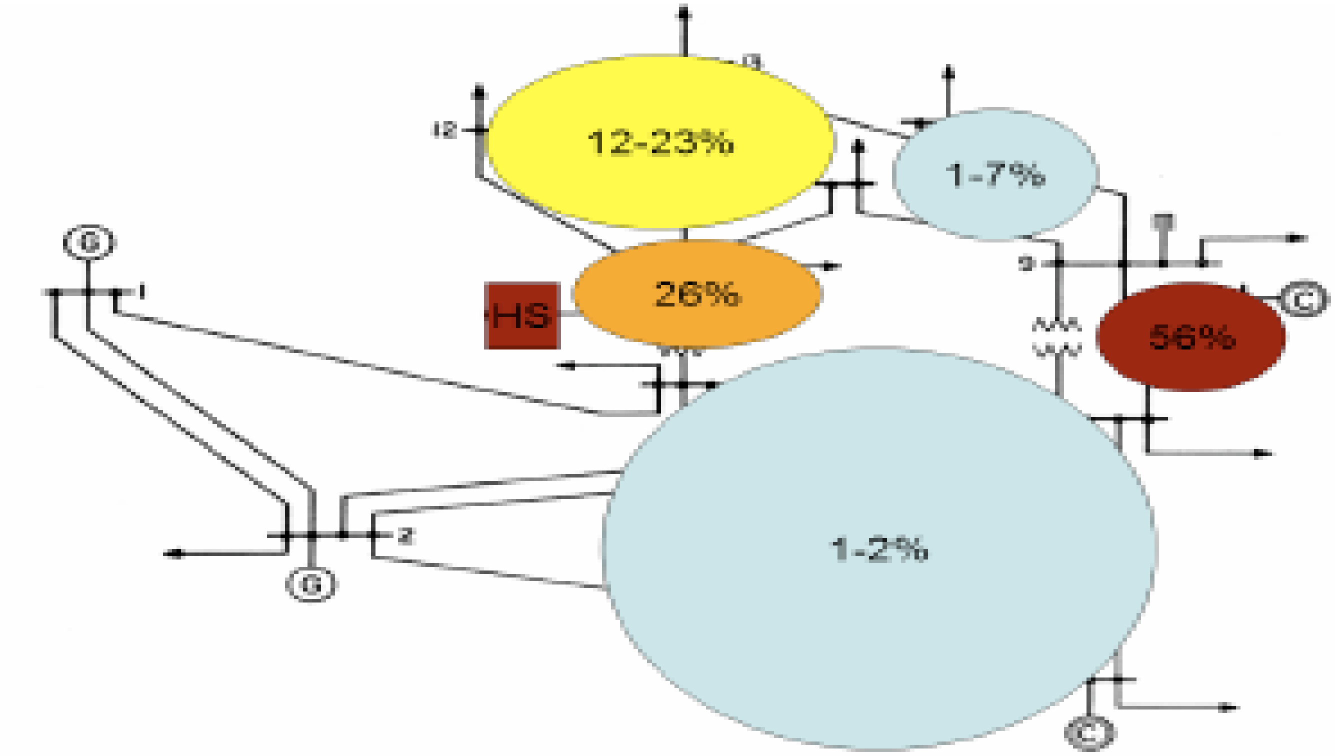



Fig. 5. Propagation of the 5th harmonic in Case II.

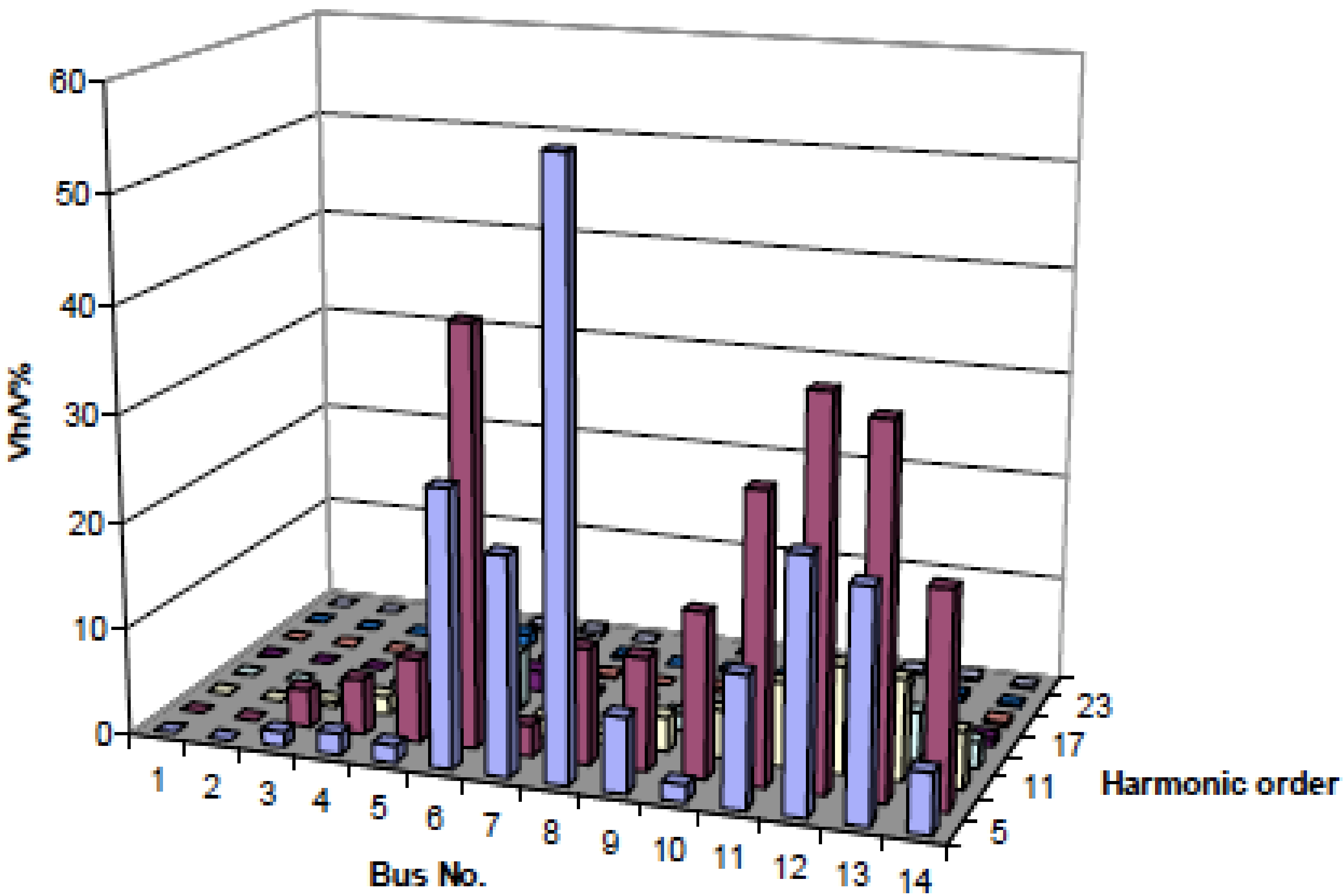



Fig. 4. The percentage of harmonic voltage to normal voltage in Case II.

# Harmonic source at bus 8

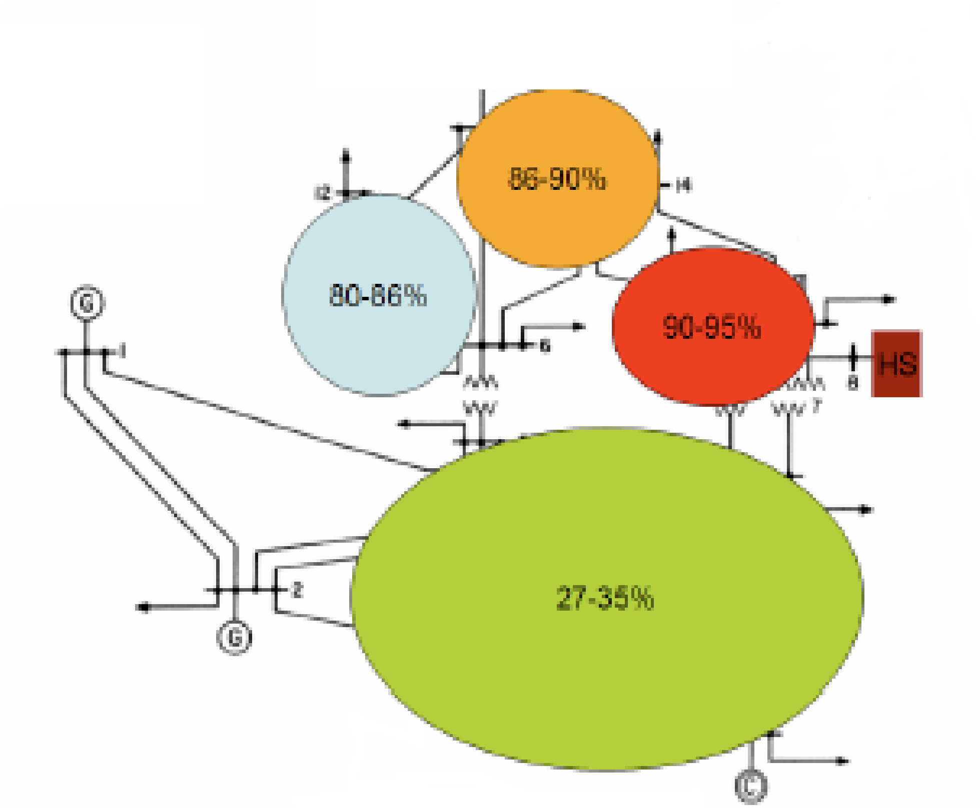



Fig. 7. Propagation of the 5th harmonic in Case III.

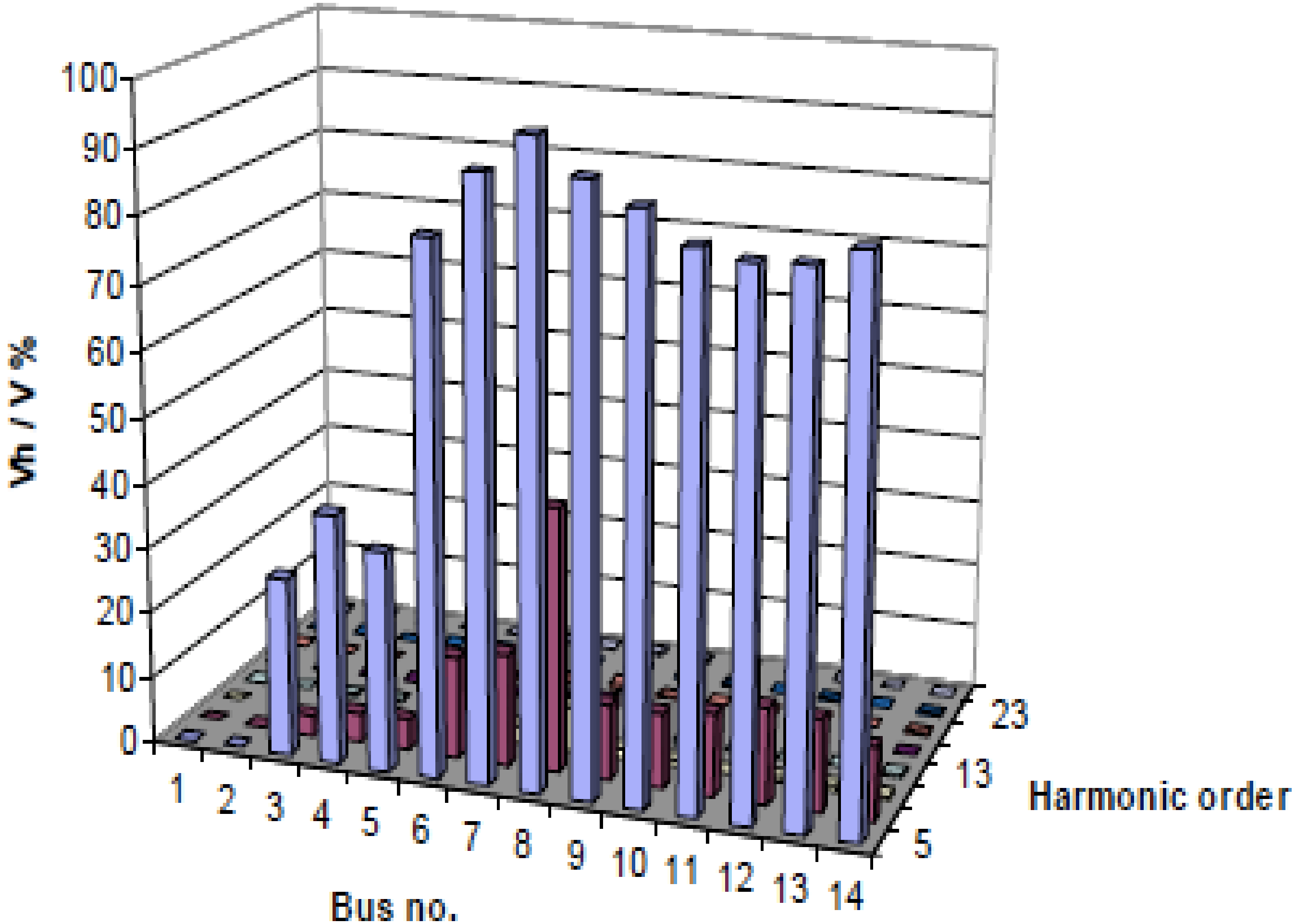



Fig. 6. The percentage of harmonic voltage relative to normal voltage in Case III.

# Transfer impedance as a metric of distortion propagation (network interactions)

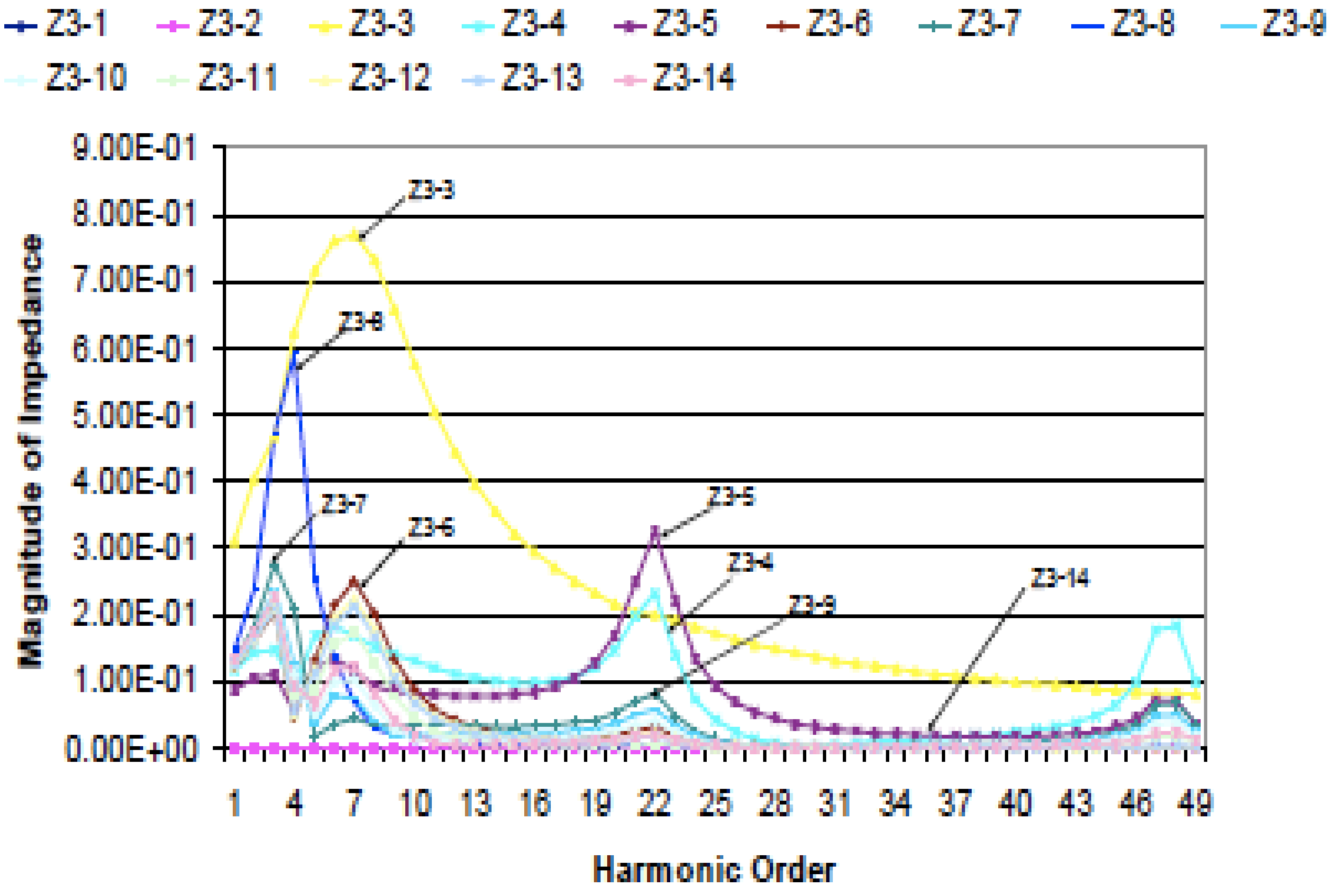



Fig. 8. The magnitude of the impedance between bus no.3 and all buses.

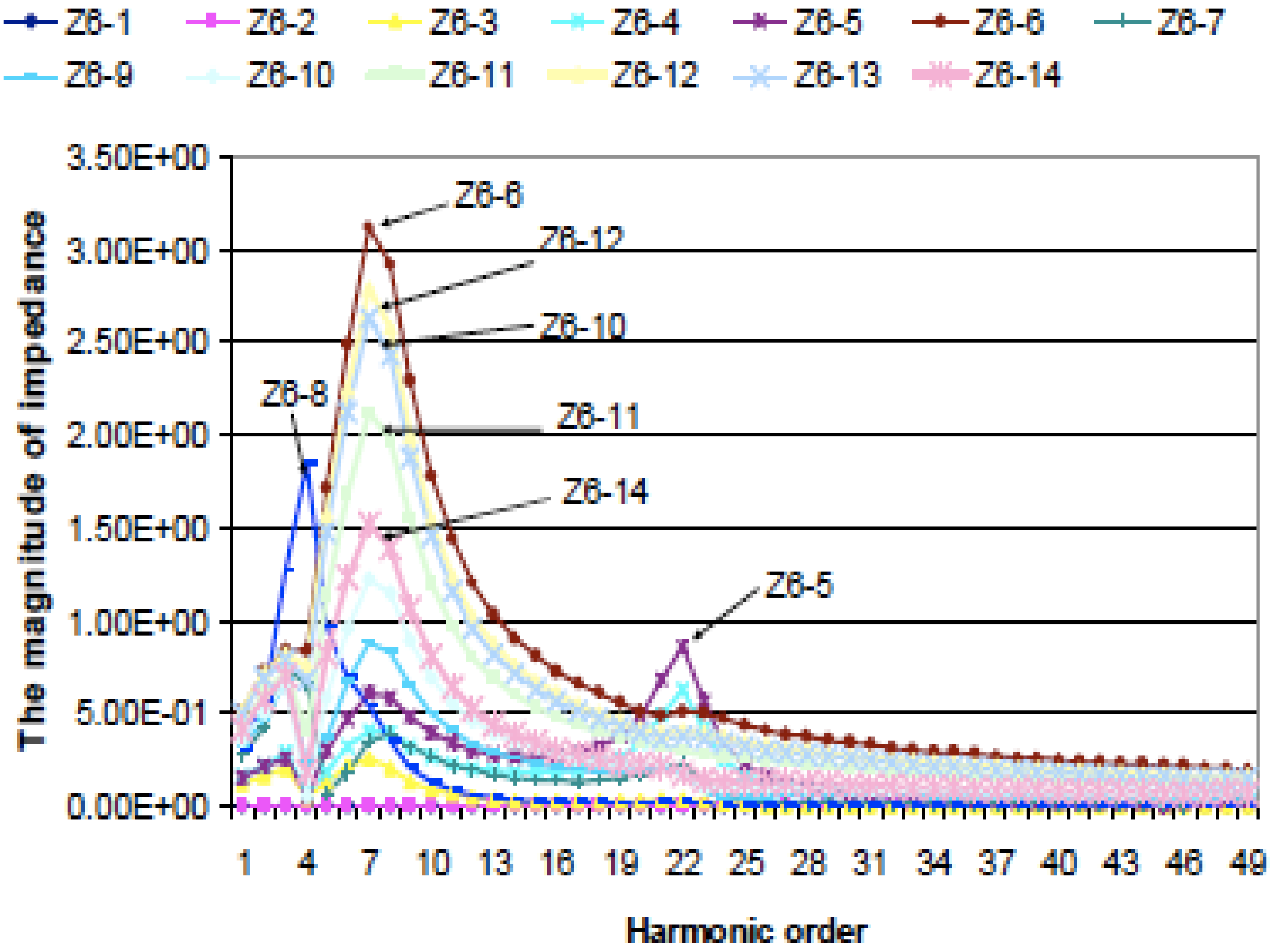



Fig. 9. The magnitude of the transfer impedance of bus no.6 and all buses.

# Issues with safety standards for preventing harmonic resonance

- Standards for avoiding system-level safety problems difficult to define
- System-dependent; disturbance-dependent.
- Should the standard for preventing harmonic resonance-related safety problems require filters at the source of harmonics only?
- Should the standard for preventing harmonic resonance-related safety problems be system dependent?

# Issues with standards for preventing SSR-related safety problems [3,4]

ALLEN *et al.*: EFFECTS OF TORSIONAL DYNAMICS

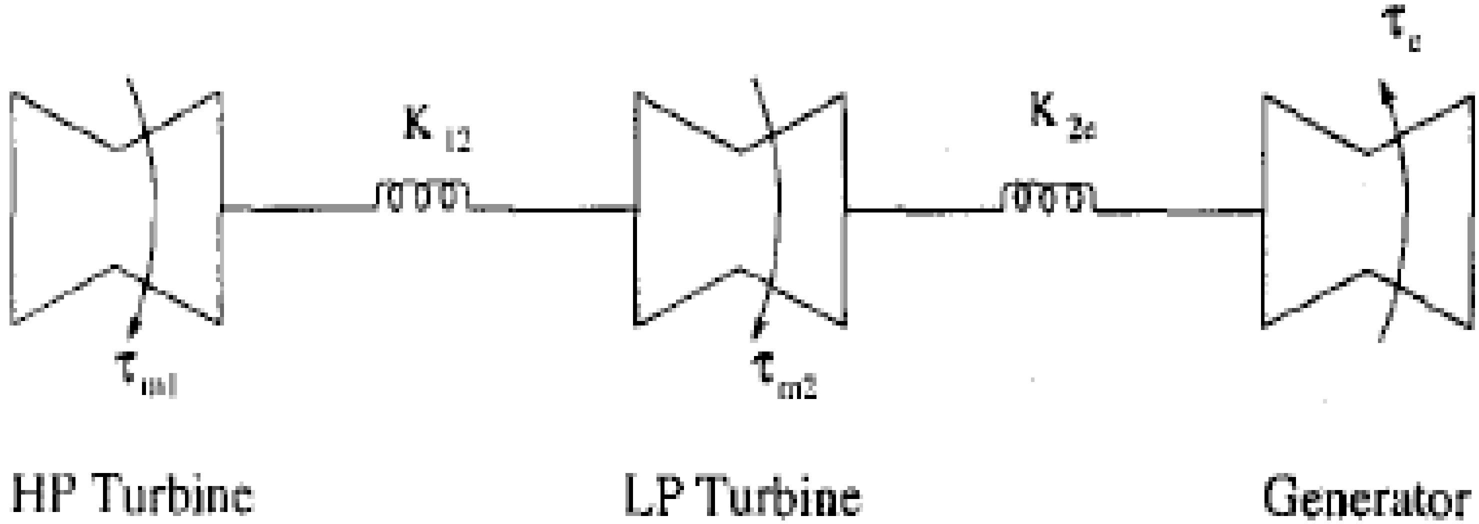



Fig. 1. The torsional spring-mass model.

# Modeling matters..

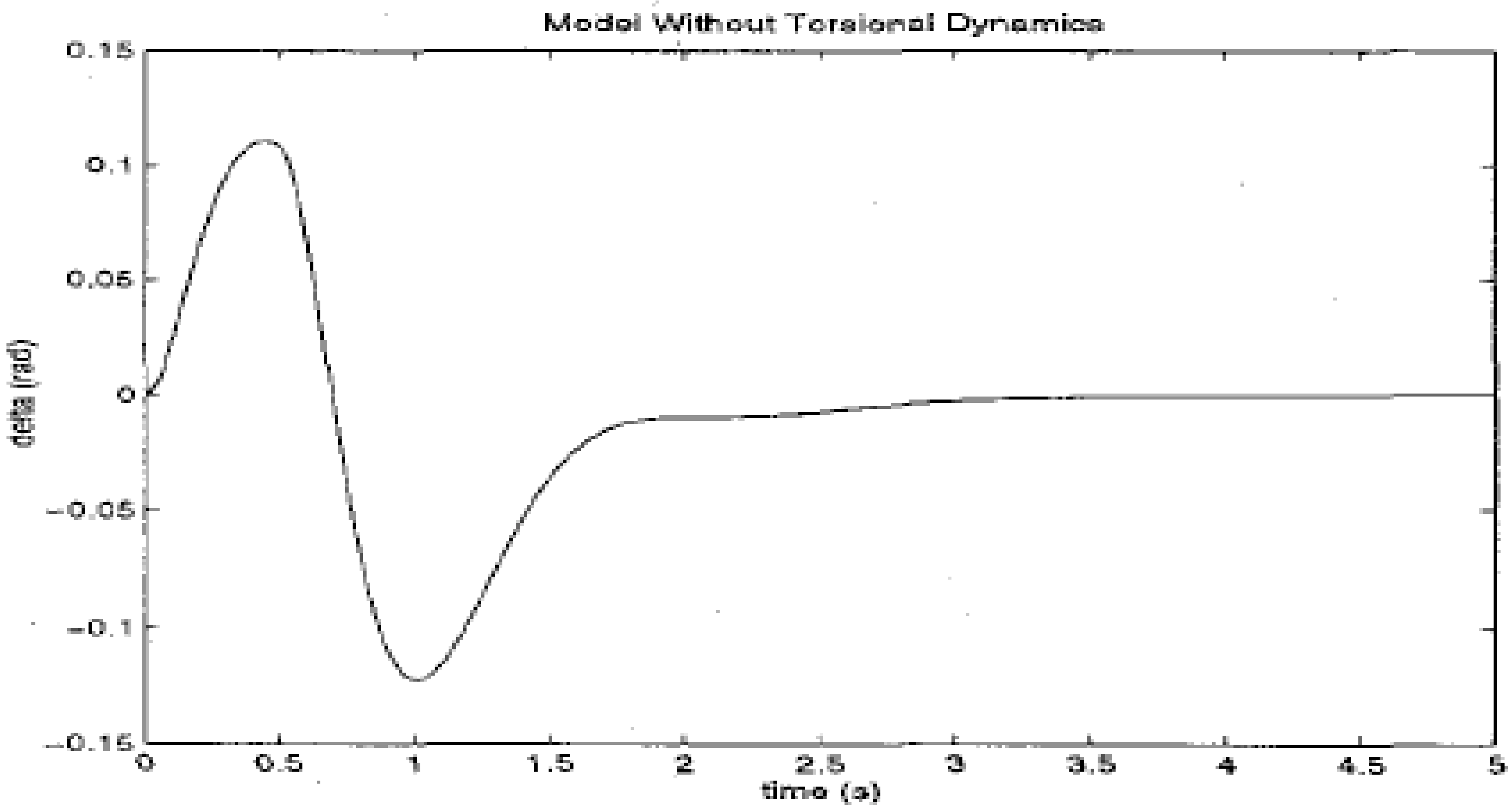



Fig. 2. Response of $\delta - \delta_o$ to a 0.5 s fault without torsional modeling.

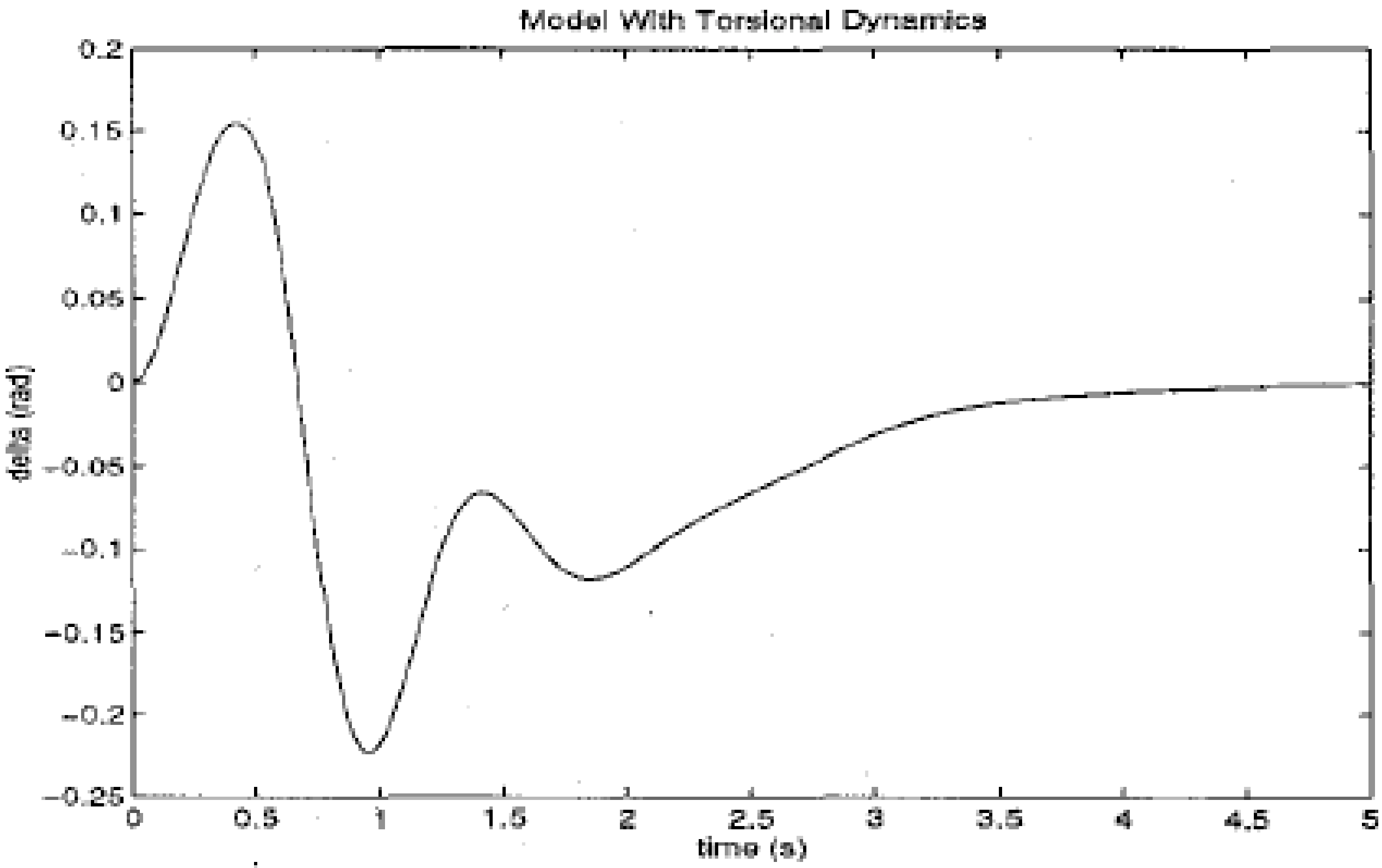



Fig. 3. Response of $\delta - \delta_o$ to a 0.5 s fault with torsional modeling. The torsional dynamics affect the response of $\delta$, although $\delta$ still returns to equilibrium within a reasonable time.

# Shaft acceleration

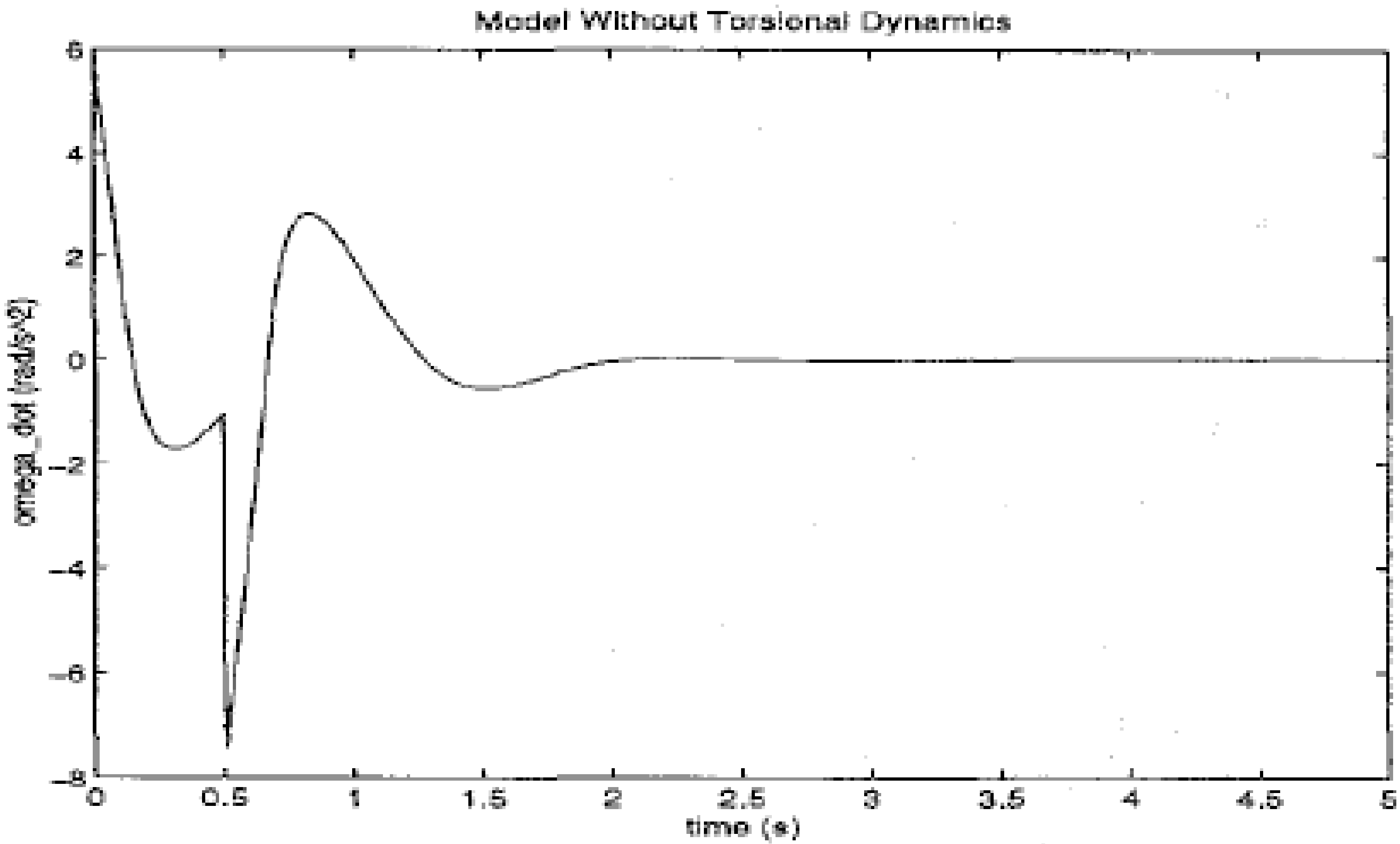



Fig. 4. Response of $\dot{\omega}$ to a 0.5 s fault without torsional modeling.

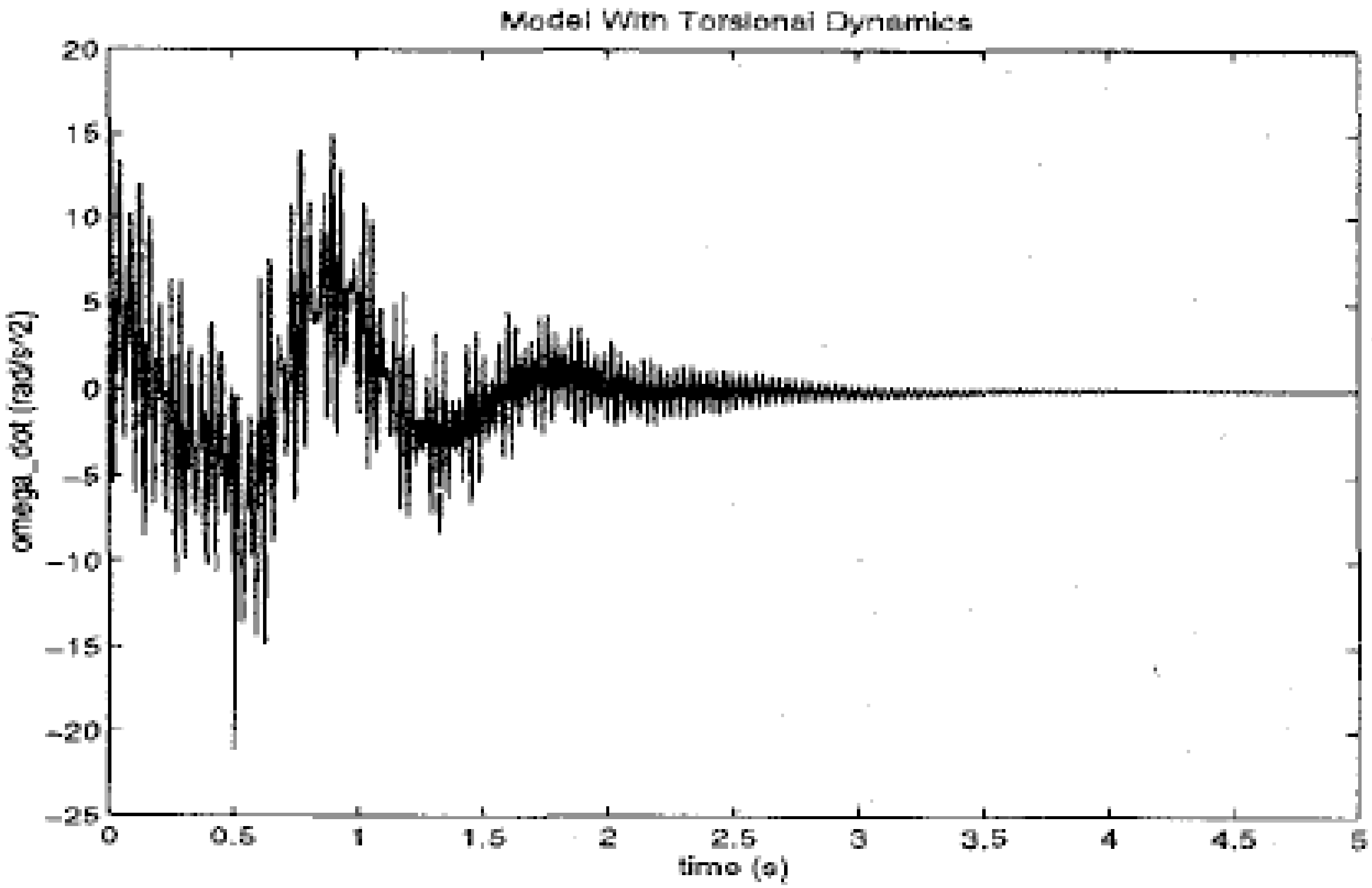



Fig. 5. Response of $\dot{\omega}$ to a 0.5 s fault with torsional modeling. The shaft oscillations form a large portion of the acceleration measurement.

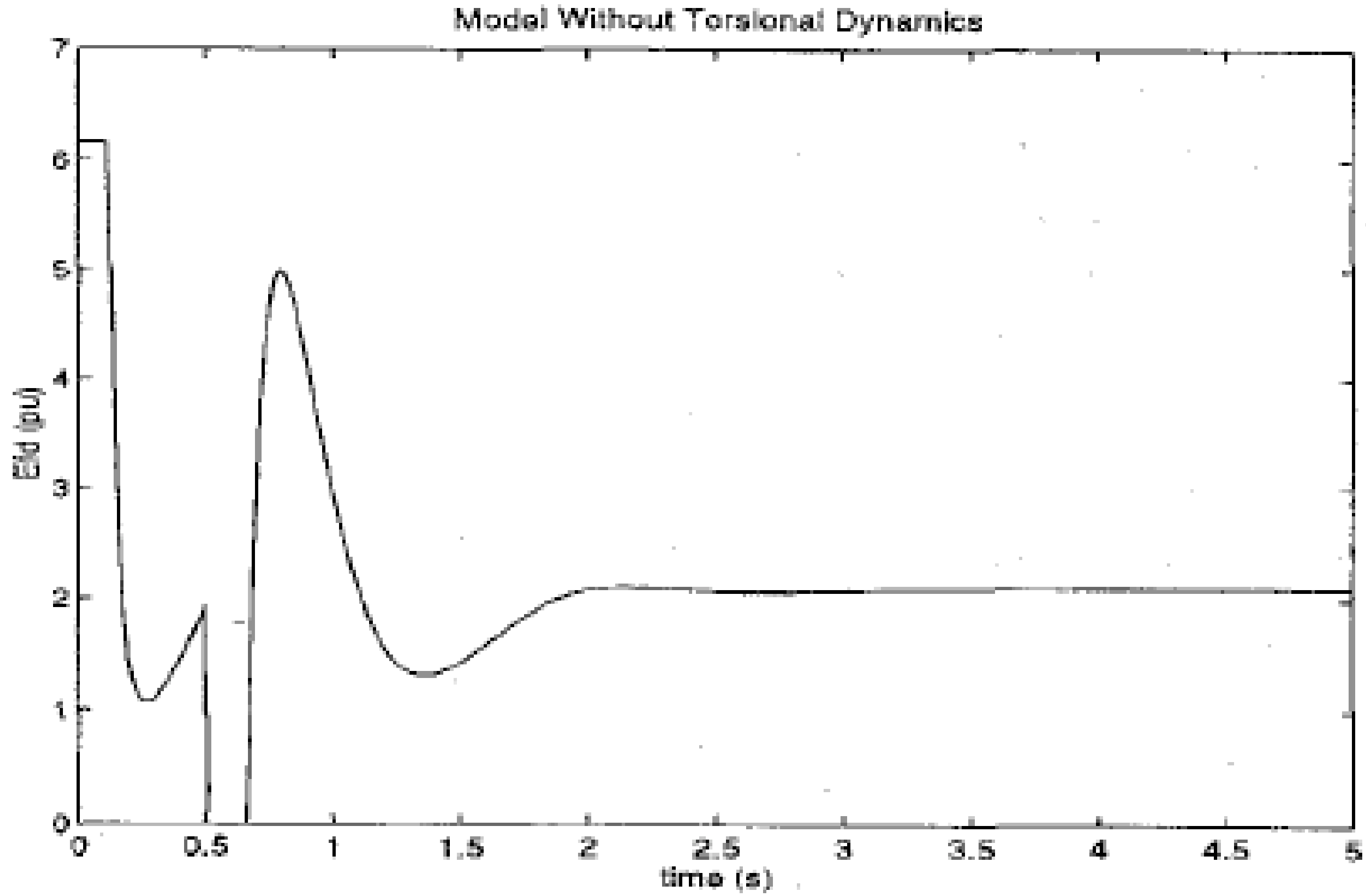



Fig. 6. Response of $E_{fd}$ to a 0.5 s fault without torsional modeling. $E_{fd}$ only saturates briefly following a disturbance.

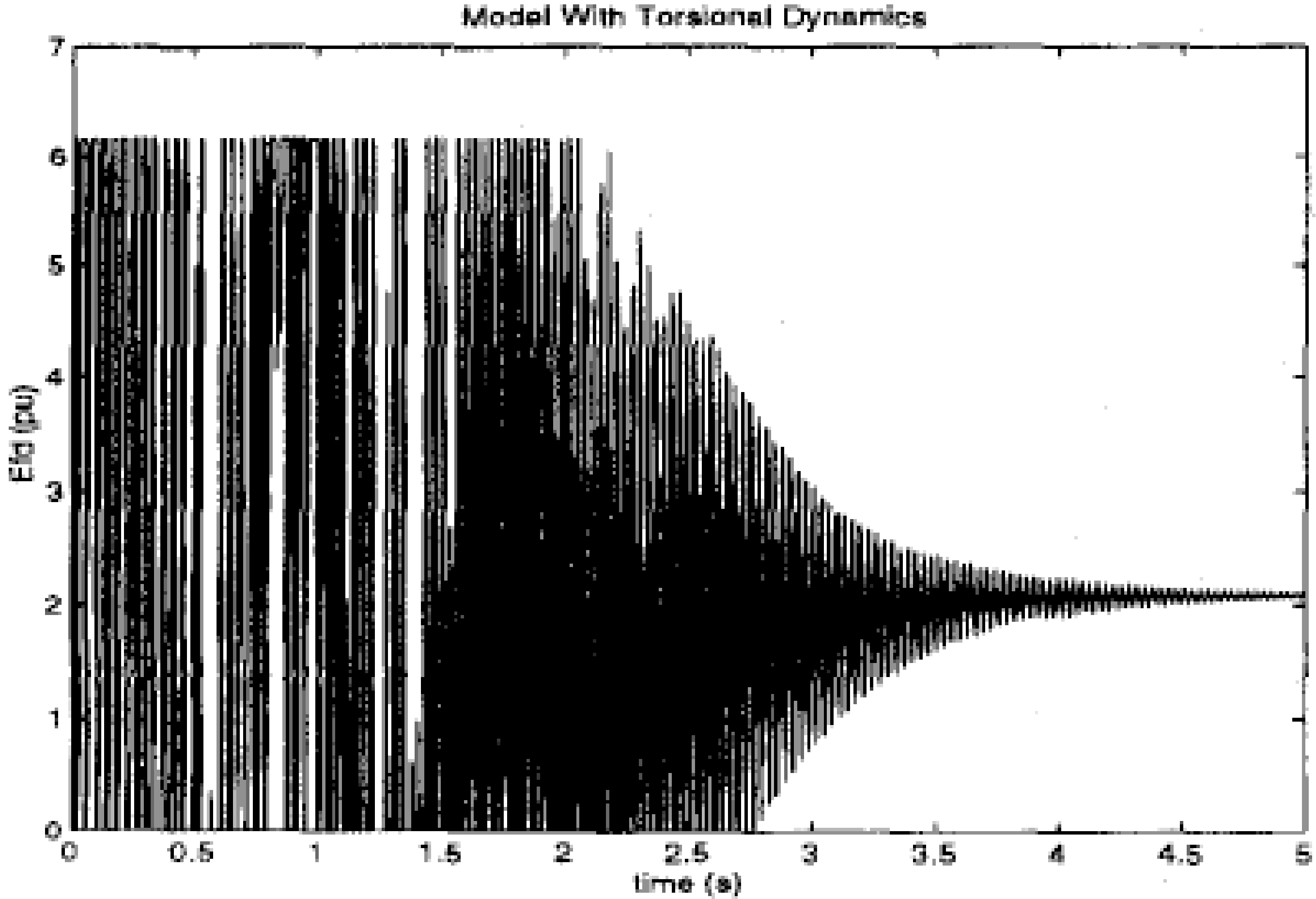



Fig. 7. Response of $E_{fd}$ to a 0.5 s fault with torsional modeling. Clearly, the torsional dynamics cause $E_{fd}$ to saturate for an extended period following the disturbance.

# Clever control (FBLC) makes the difference…

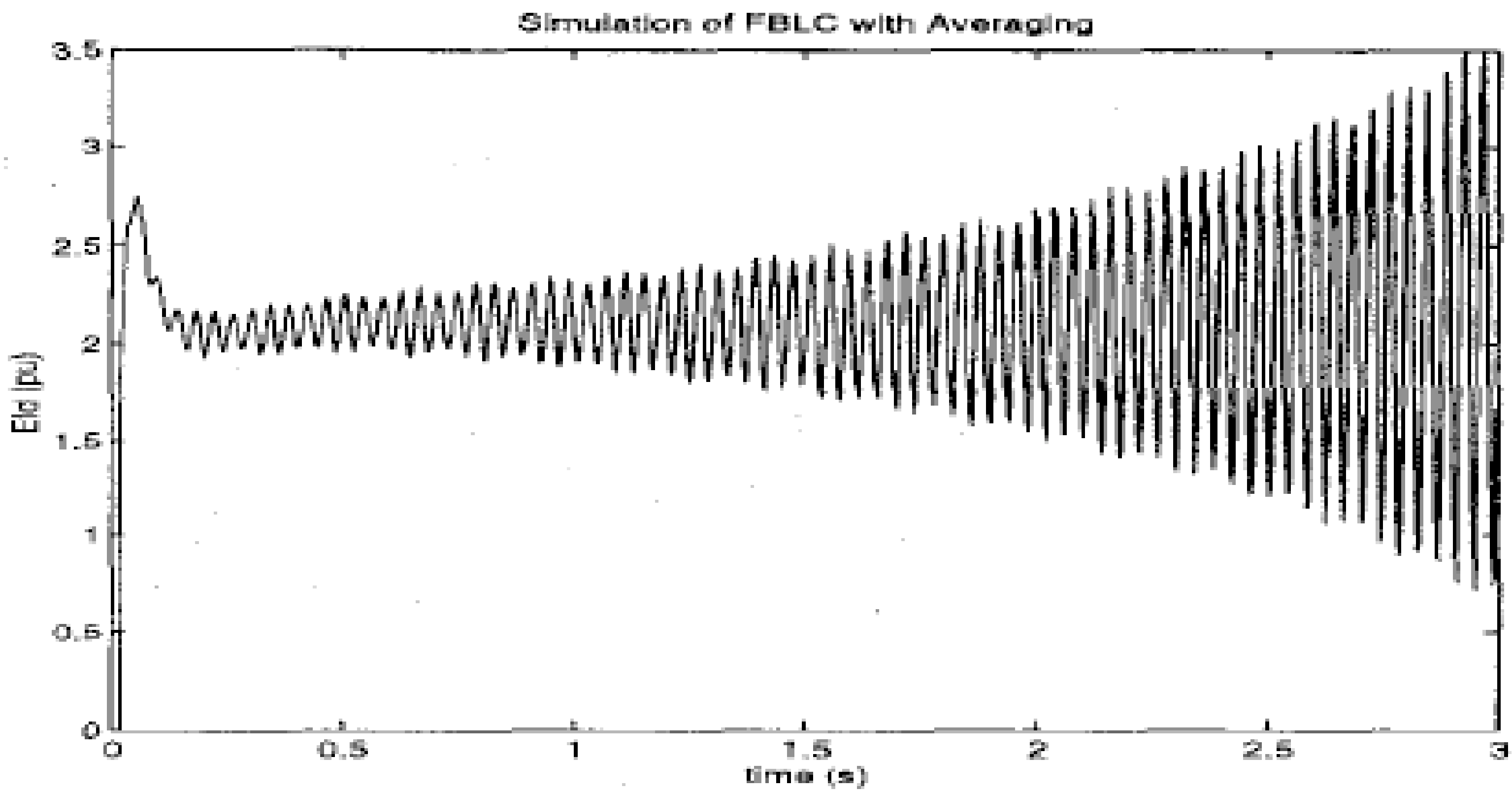



Fig. 8. Simulated response of $E_{fd}$ to a small disturbance with averaged FBLC.

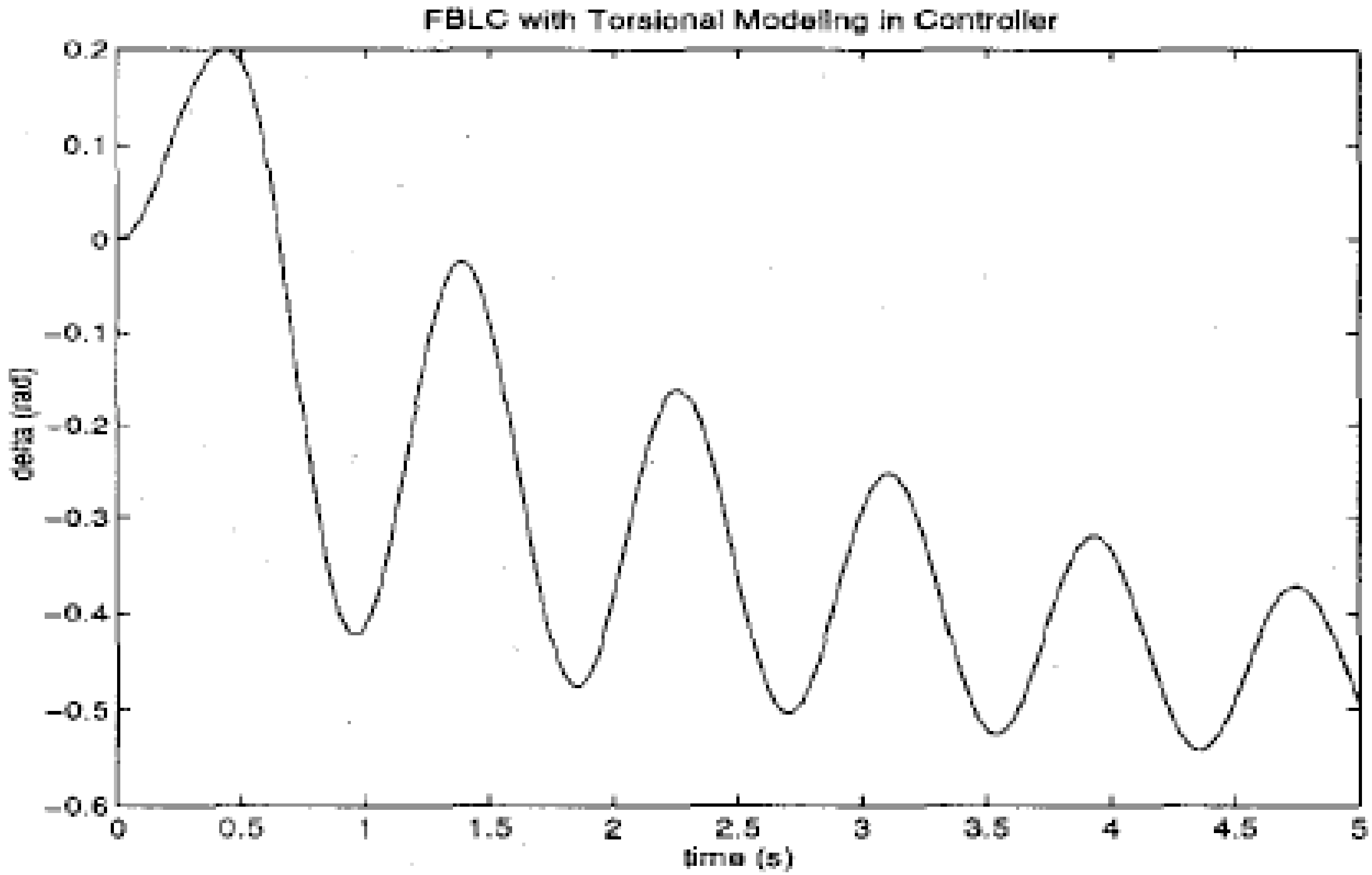



Fig. 12. Simulated response of $\delta - \delta_0$ to a 0.5 s fault with FBLC that accounts for torsional oscillations.

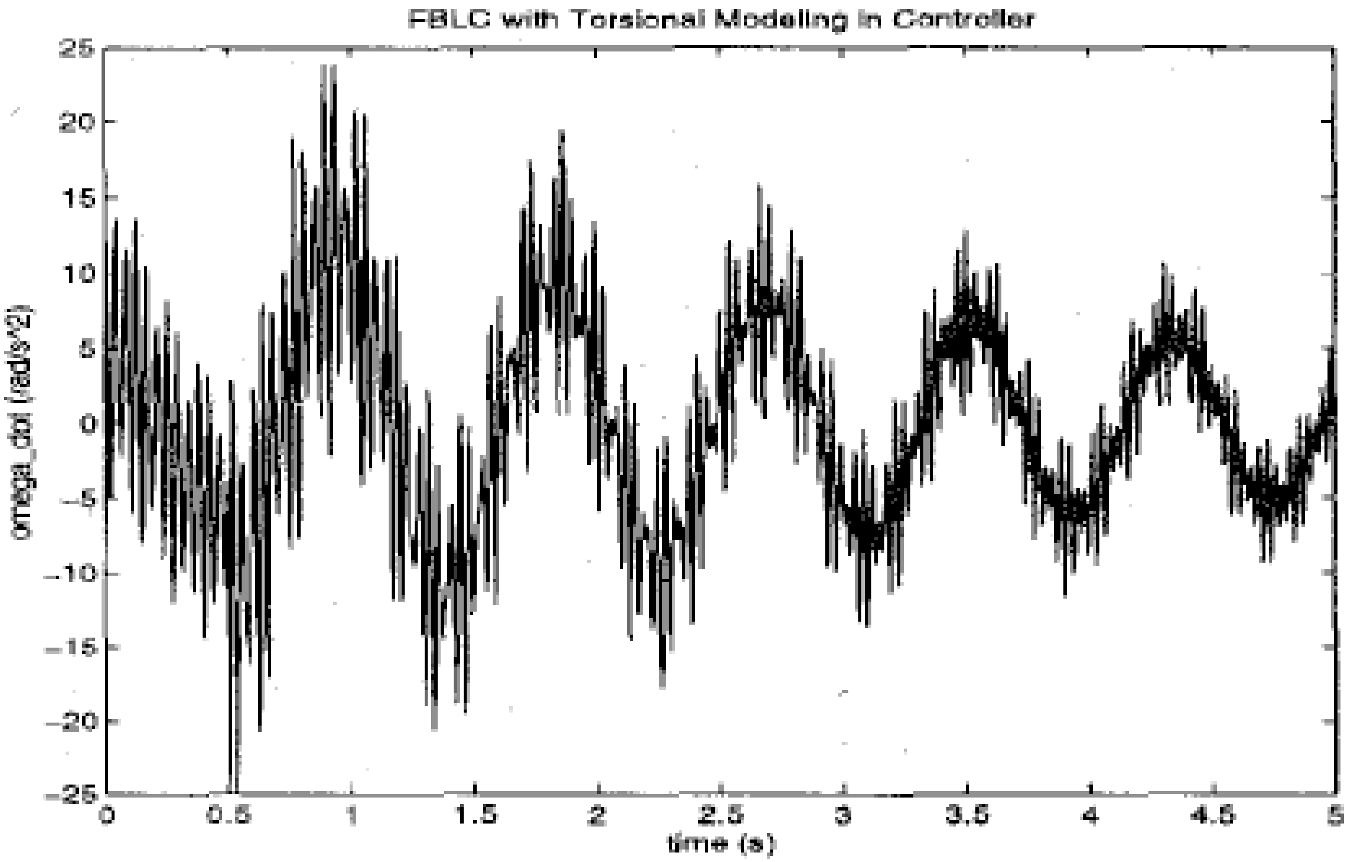



Fig. 13. Simulated response of $\dot{\omega}$ to a 0.5 s fault with FBLC that accounts for torsional oscillations.

# High-gain control for preventing SSR

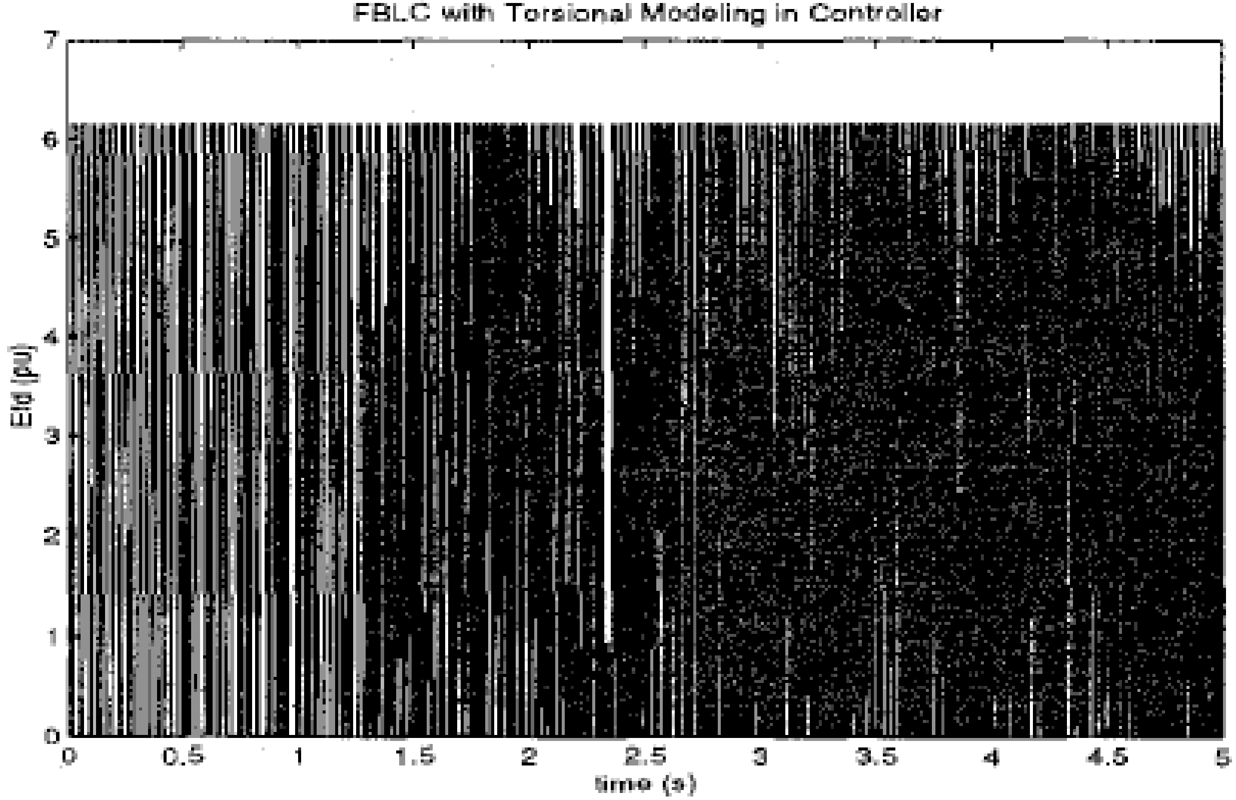


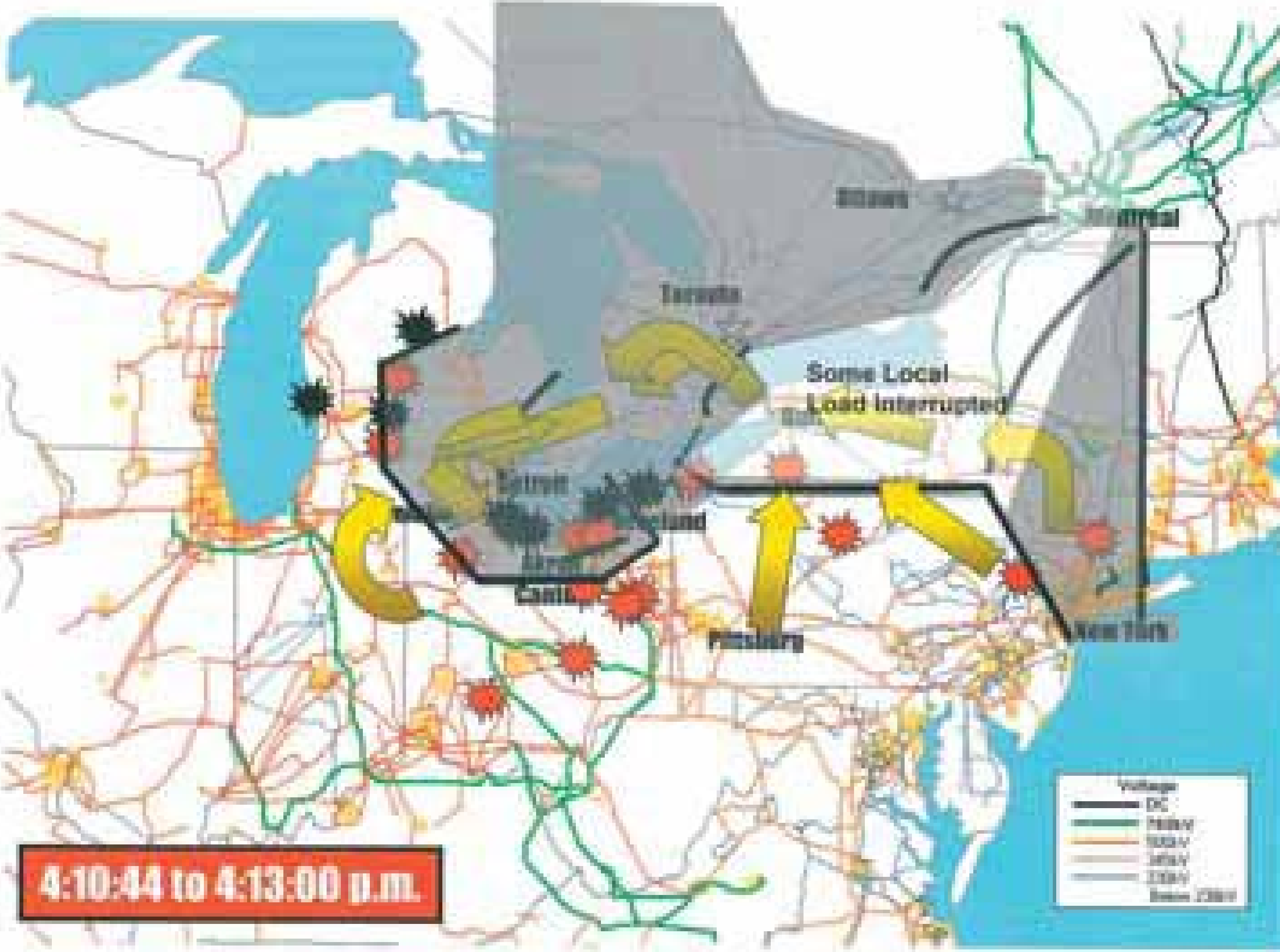

Fig. 14. Simulated response of $E_{fd}$ to a 0.5 s fault with FBLC that accounts for torsional oscillations.

# Huge issues with SSR-related safety

- Protection for avoiding SSR problem versus closed-loop control design for **decoupling interactions between different components**.
- It is much more effective not to limit the line parameters.
- Protection for SSR at its infancy, and has worse performance than nonlinear decentralized FBLC for Efd of a generator.
- **High-gain power electronically-controlled SSR very beneficial in this case.**
- The key challenge: How to set the ``best” standard to induce its deployment instead of using protection for disconnecting the affected component.

# Issues with standards for ensuring AC synchronism

- Many root causes of instabilities in today's industry (large equipment failures, large deviations in system load away from the conditions for which the primary controllers are tuned) [5,6]
- Newly evolving transient stability problems in response to sudden prolonged wind gusts [7,8]
- Small-signal robustness problems [9,10]


Some Local
Load Interrupted
4:10:44 to 4:13:00 p.m.

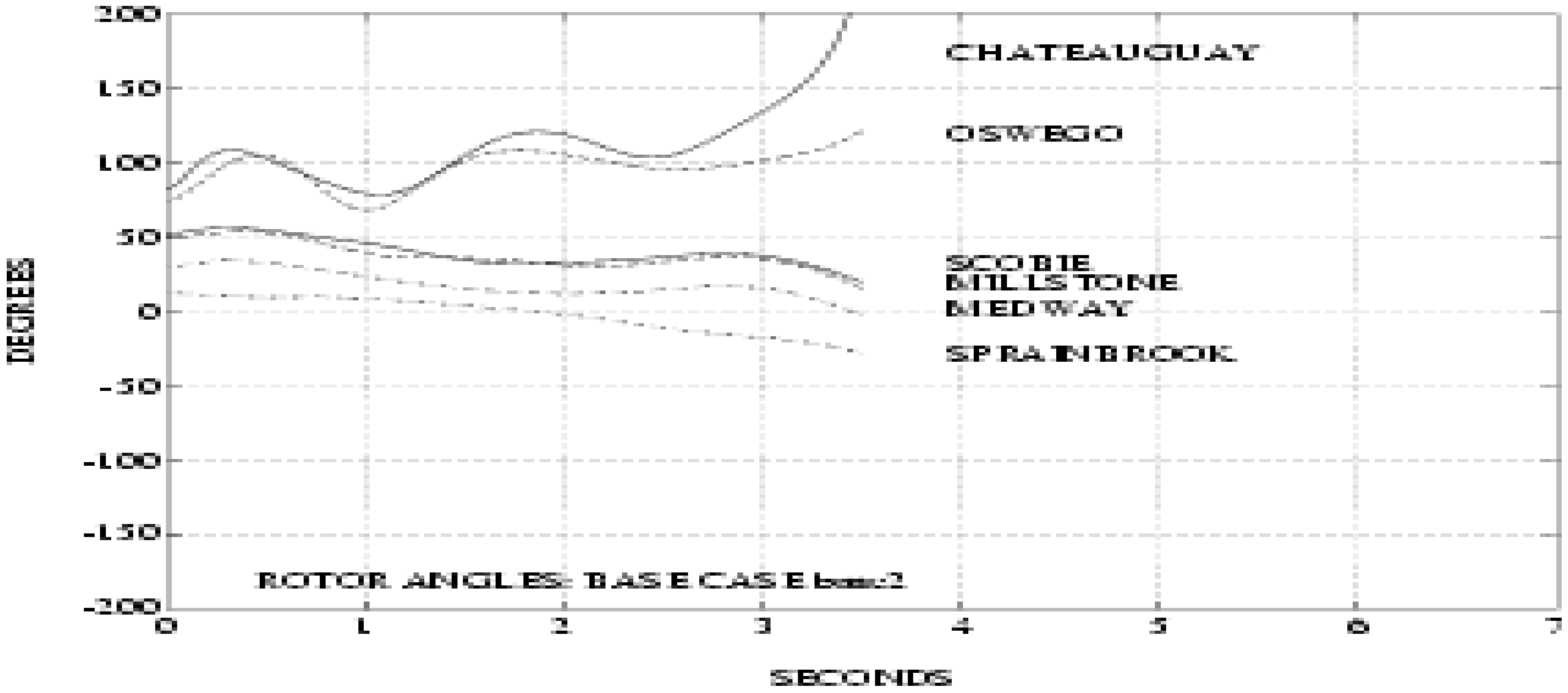
# Possible role of enhanced control during abnormal conditions [5,6]

- Adjust logic of primary controllers to avoid instability problems;
- Systematic coordination of the remaining resources to prevent steady-state imbalances and additional congestion (adjust settings on voltage support equipment, adjust power generated to avoid imbalances) [12]

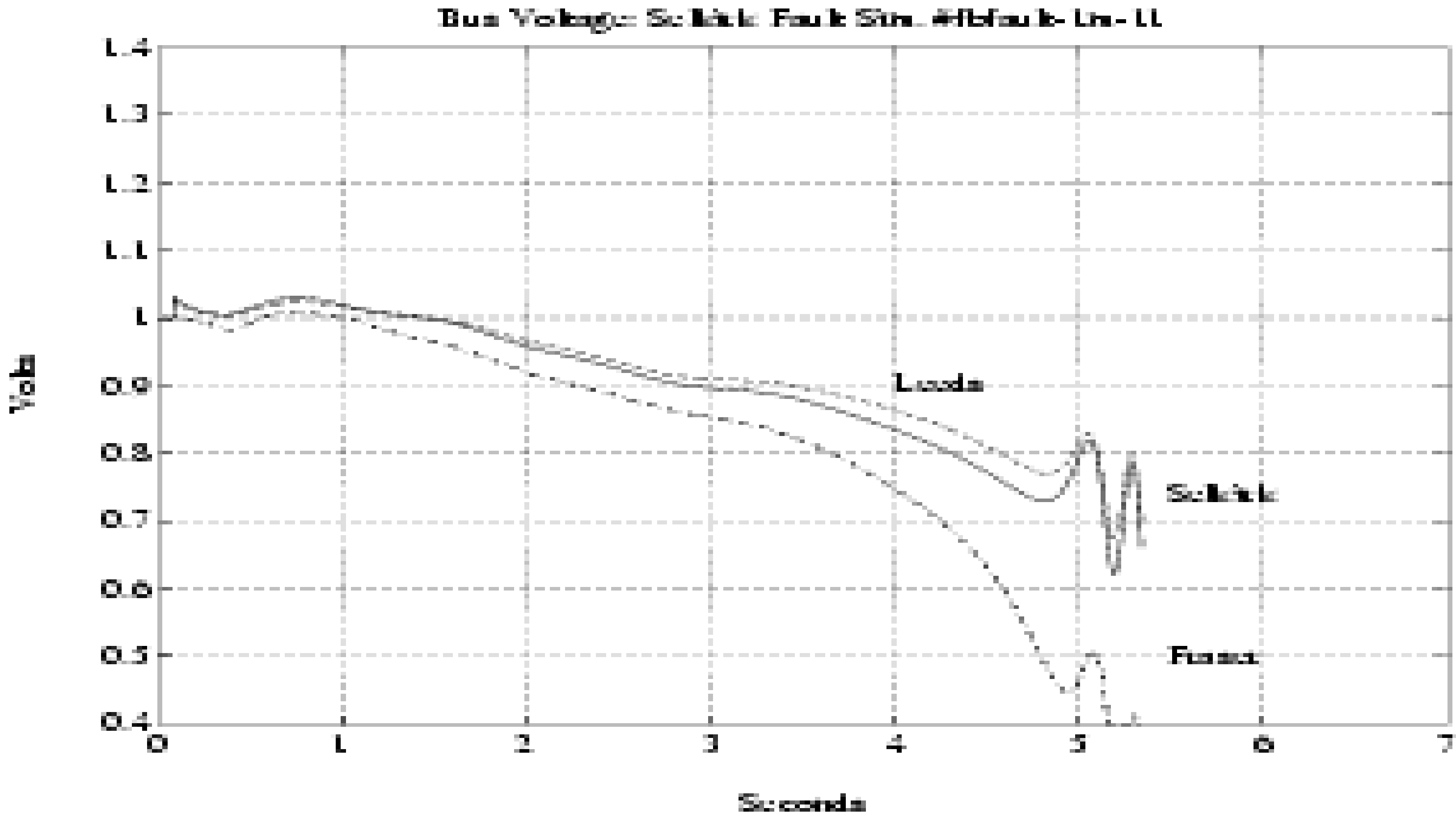
# Potential of novel stabilizing controllers for preserving system integrity [5,6]

- A 38-bus, 29 machine equivalent dynamic model of the NPCC system
- It was shown to reproduce a multi-machine oscillation that occurred at .75Hz, involving groups of machines in NYC (modeled as Sprainbrook generator) and the northeastern part of New York State, as well as parts of Canadian power system (modelled primarily by the Oswego and Chateaguay units);
- The fault scenario selected for this test was a five-cycle three-phase short circuit of the Selkrik/Oswego transmission line carrying 1083MW. The oscillation grows until the Chateaguay generator loses synchronism, followed shortly by the Oswego unit.

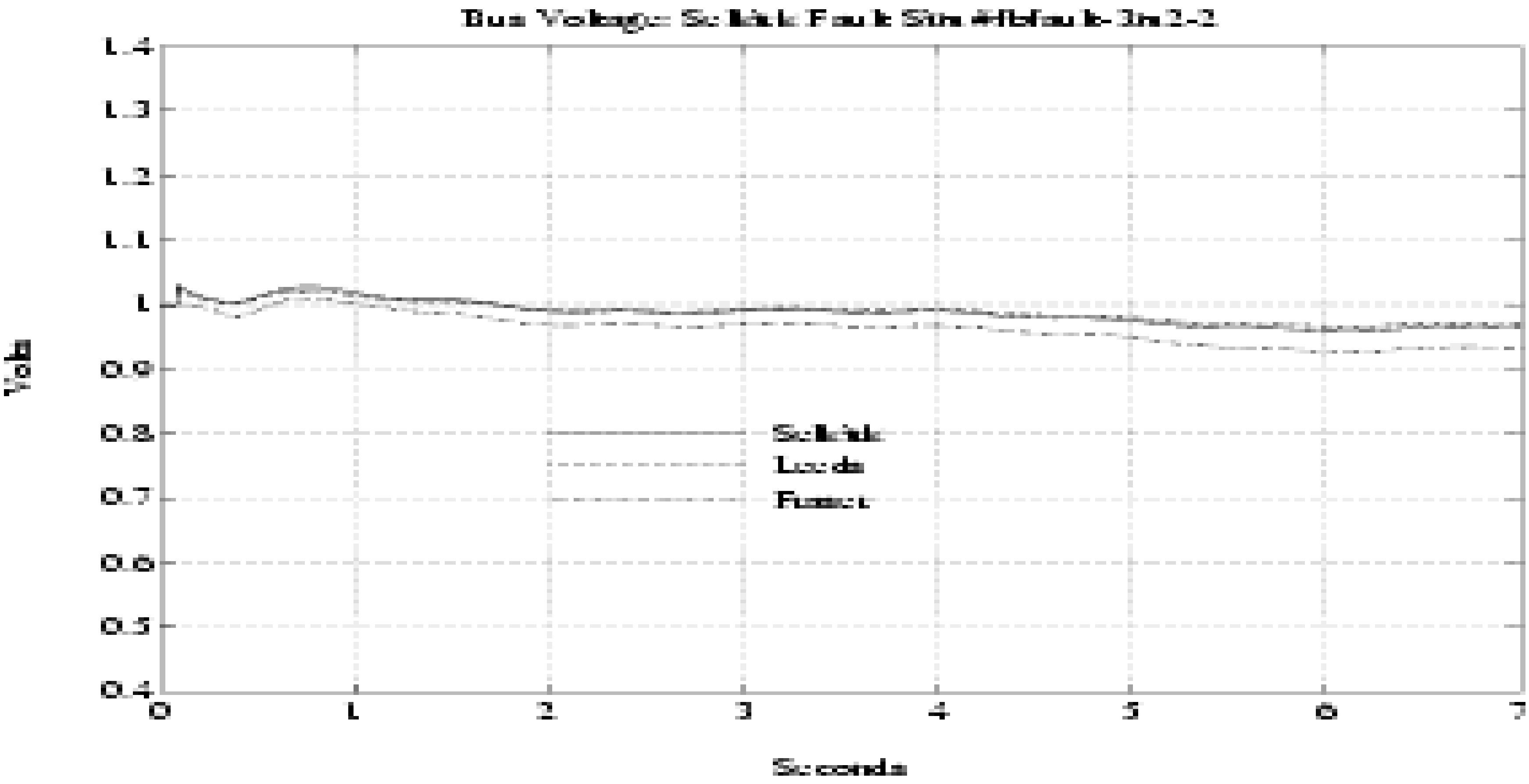
# Rotor angles -- base case for Selkrik fault



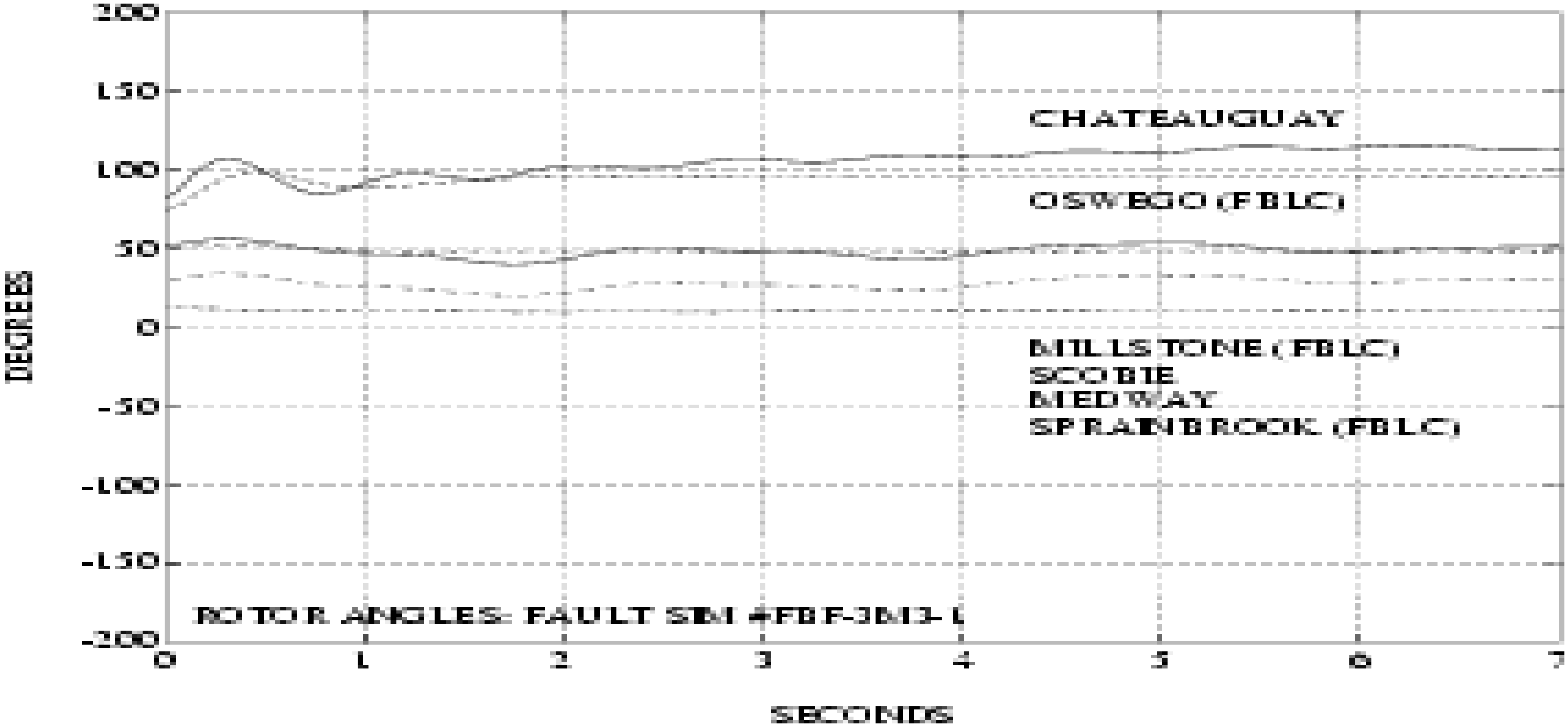
# Voltage response with conventional controllers-base case Selkrik fault



# Bus voltages with new controllers [5,6]



# Rotor angle response with the new controllers (FBLC+ODSS) [5,6]



# Summary of potential of FBLC+ ODSS controllers

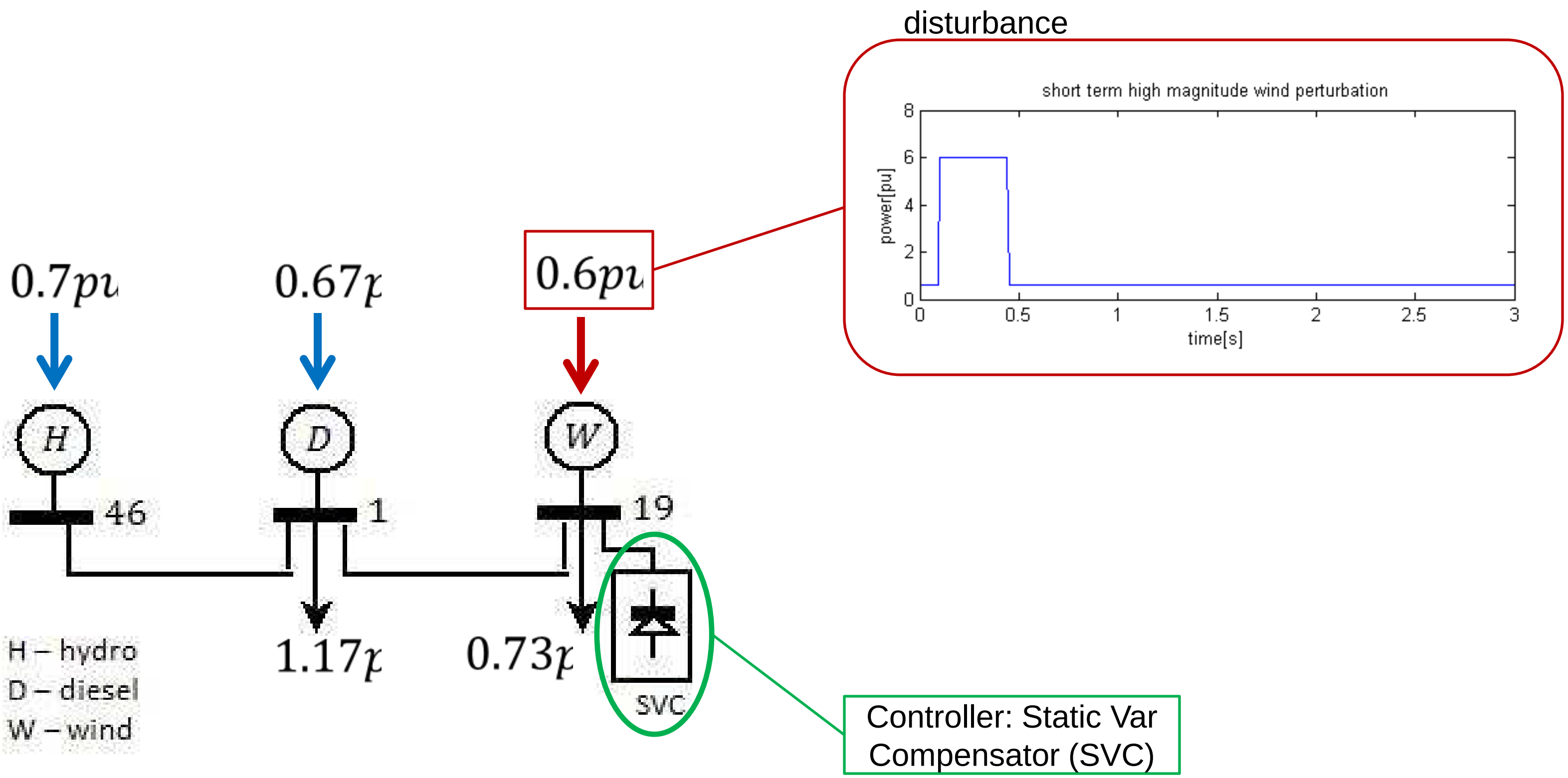
- It is possible that these controllers could avoid loss of synchronism while the conventional controllers can not
- It also was shown that the same controllers are ideal for preventing sub-synchronous resonance [3]
- Therefore critical to consider while designing SPS of the future
- No fast communications required. Therefore simple to implement.

# Possible ways of adapting primary controllers

- More adaptive decentralized controllers (various nonlinear high-gain controllers—sliding mode control; feedback-linearizing control (FBLC); observation decoupled state space combined with FBLC logic)
- A combination of coordinating signals and change of logic (coordinating signals identifying when the system response is qualitatively different and it requires change in control logic in order to stabilize dynamics)
- NONE OF THE CURRENTLY IMPLEMENTED CONTROLLERS ARE CURRENTLY AFDAPTIVE except the multi-modal Hydro-Quebec PSS)

# Issues with stability standards for managing high wind gusts [7,8]

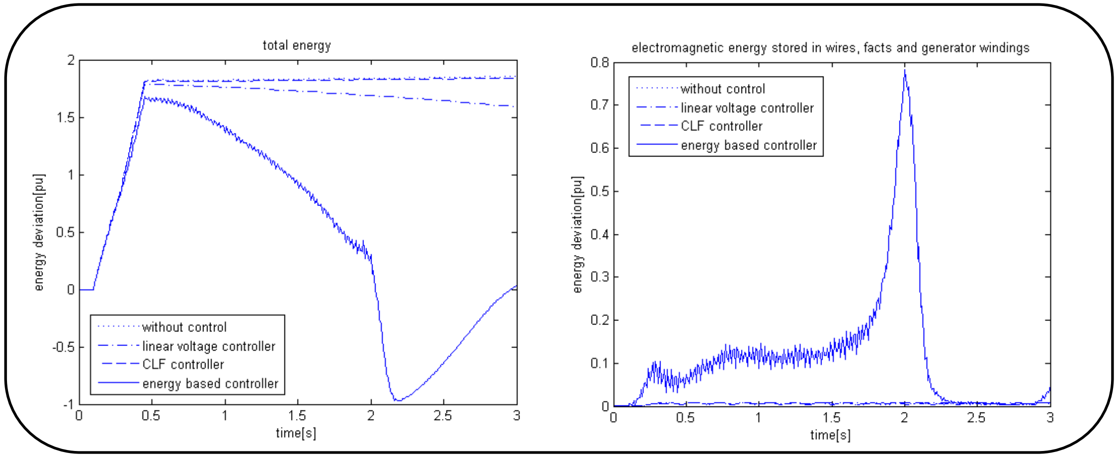
- High wind surges in Flores Island



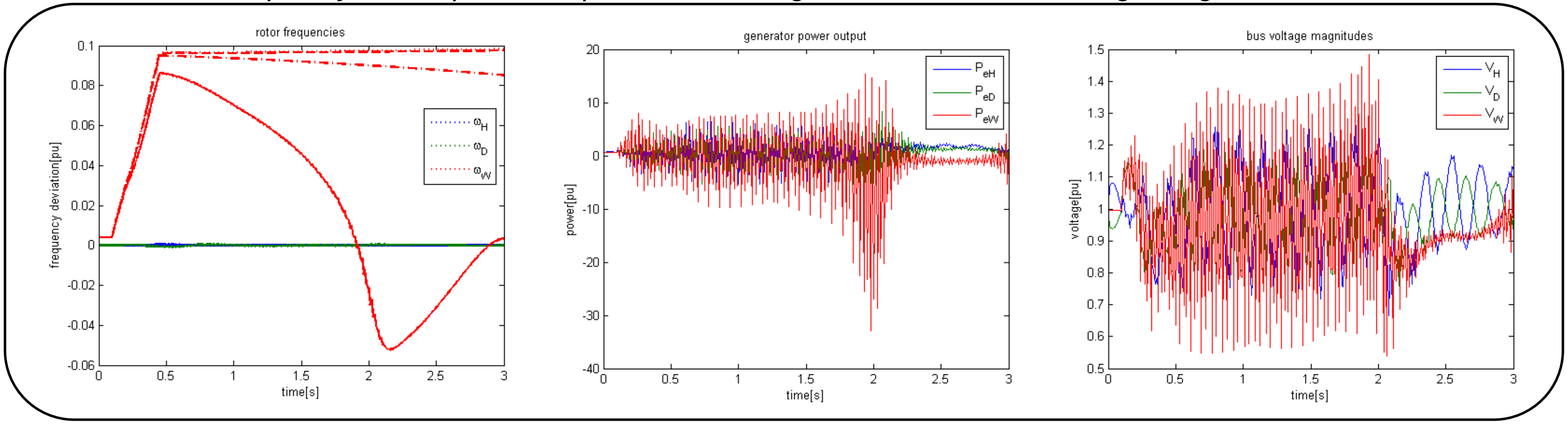
# Stabilization using high-gain switching

- Hydro
- Diesel
- Wind
- Other control strategies

Total accumulated energy and energy accumulated in wires




Rotational frequency, active power output of the three generators and bus voltage magnitudes



# Modeling & Control

- Use of **time varying phasors for transmission line and FACTS modeling** to
  - Capture fast dynamics
  - Establish ODE model
- Assume fast PE thyristor switching – averaged switching model

- **Energy-Based controller** is proposed
  - Temporarily accumulates energy of disturbance in PE devices

$$\nu_C = \frac{1}{2}C(\tilde{V}_D^2 + \tilde{V}_Q^2)$$

$$\nu_L = \frac{1}{2}L(\tilde{I}_D^2 + \tilde{I}_Q^2)$$

$$\nu_{mach} = \frac{1}{2}J\tilde{\omega}^2 + \nu_{pe}(\delta) - \nu_{pe}(\delta_0) + \sum_{n_L} \nu_L$$

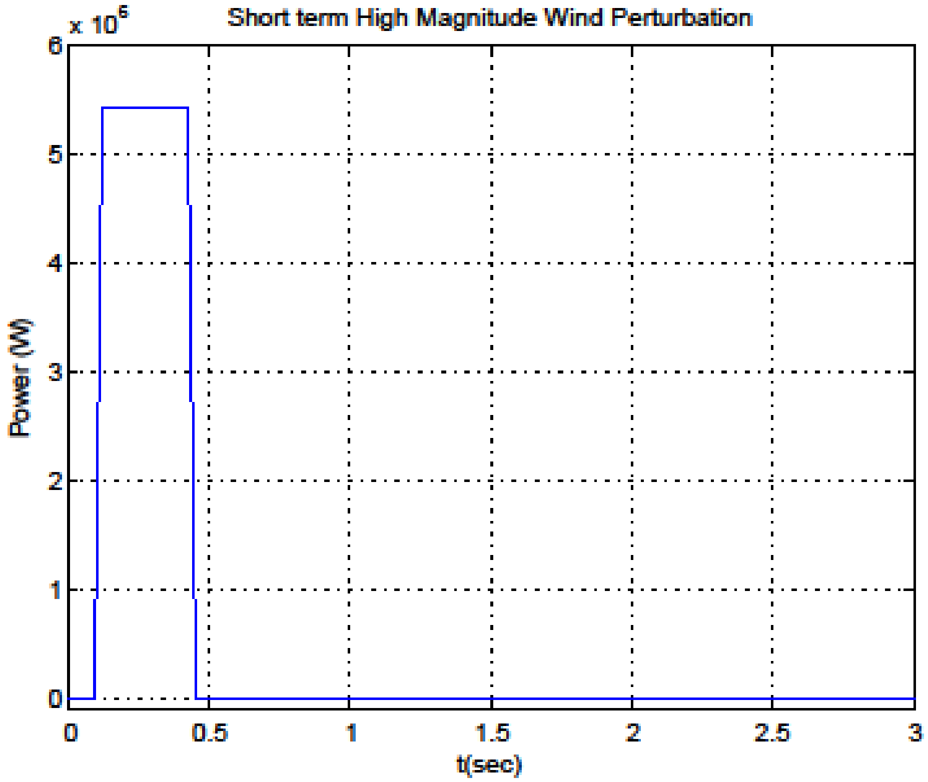
$$\begin{aligned}\nu(x) &= \sum_i \nu_{C_i}(\tilde{V}_{iD}, \tilde{V}_{iQ}) + \sum_i \nu_{L_i}(\tilde{I}_{iD}, \tilde{I}_{iQ}) + \sum_i \nu_{rot_i}(\tilde{\omega}_i, \delta_i) \\ &= \nu_{em}(x) + \nu_{rot}(x)\end{aligned}$$

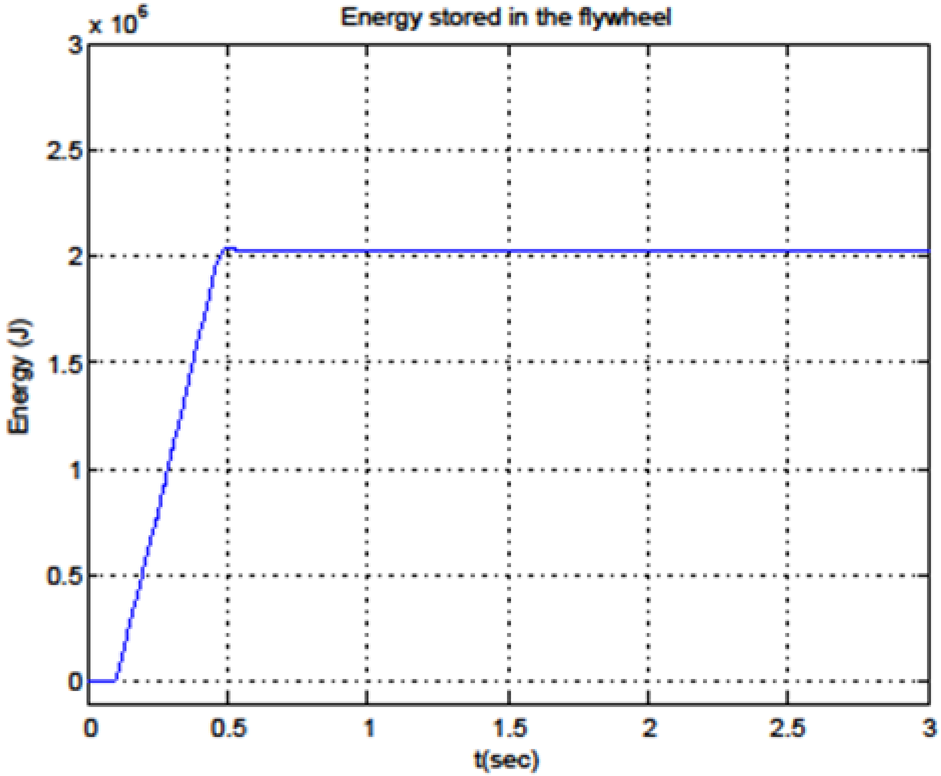
$$\begin{aligned}\dot{\nu}(x) &= \dot{\nu}_{em}(x) + \dot{\nu}_{rot}(x) \\ &= \dot{\nu}_{diss}(x) + \dot{\nu}_{exch}(x) + \dot{\nu}_{acc}(x)\end{aligned}$$

$$e(t) = \dot{\nu}^{ref}(t) - \dot{\nu}_{acc}(t) = P^{ref}(t) - \dot{\nu}_{acc}(t)$$

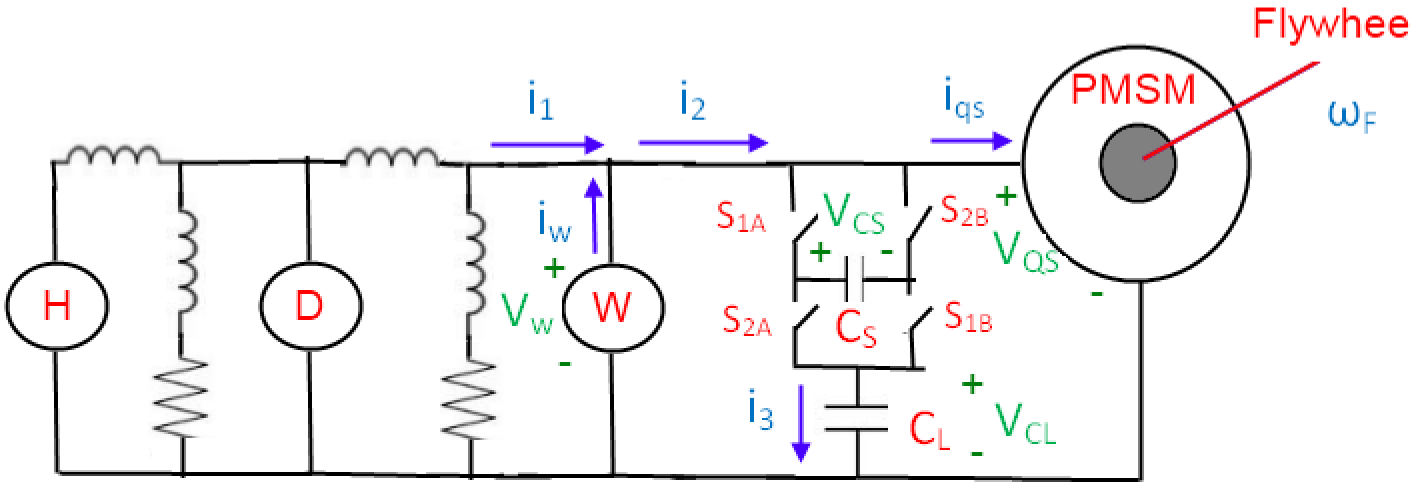
# Sliding Mode Control of Flywheel

- Treat the rest of the system as a disturbance
- Set $i_{qs}^{*} = \dfrac{2\Delta P_{wind}}{N\lambda_m\omega_f}$ ,so flywheel absorbs wind disturbance



# Dynamic Model of Entire System

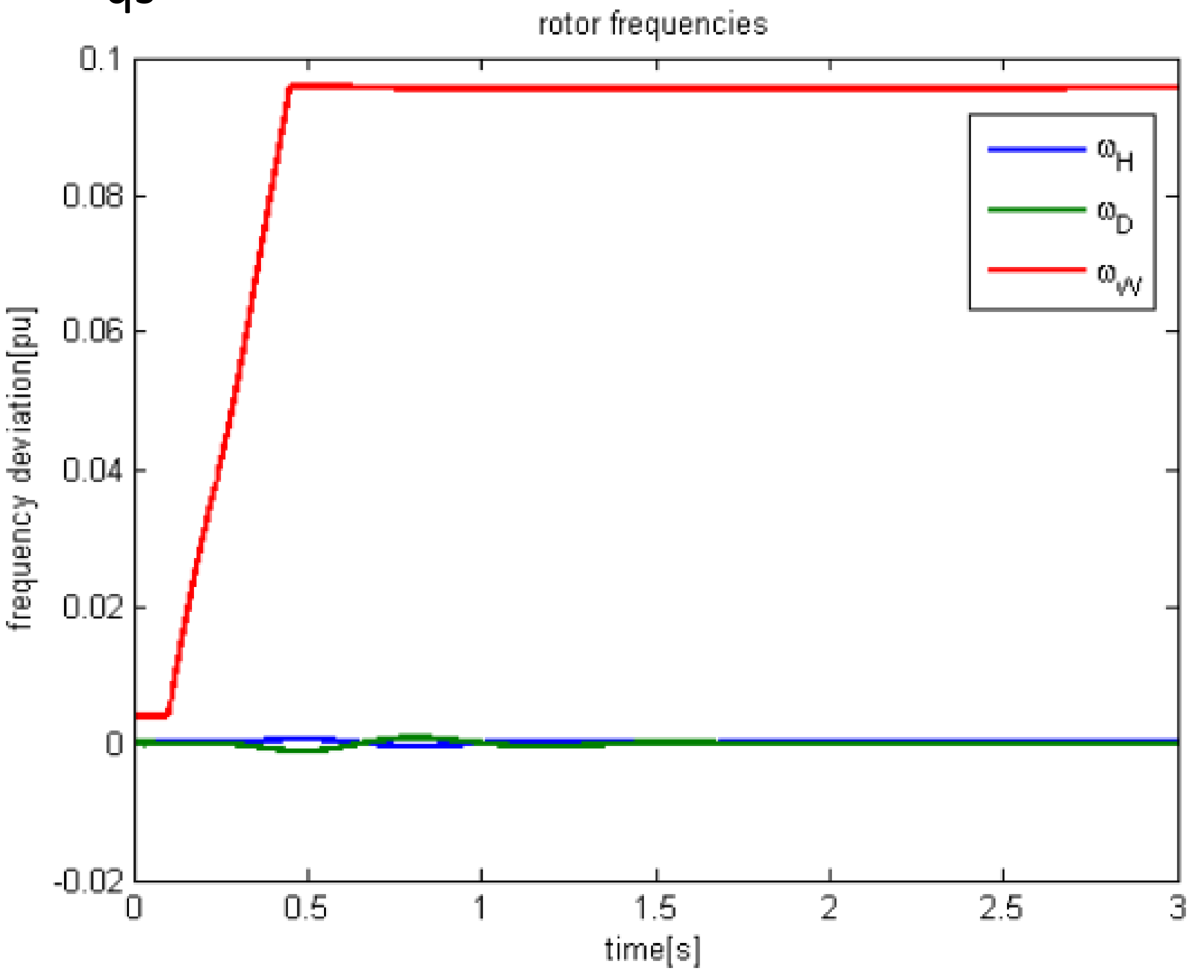



- Switches open and close at very high frequency relative to rest of the grid
- Fast time scale t and slow time-scale τ
- Using state space averaging,

$$\bar{v}_{cs}(\tau) = \frac{v_{cs}{}^{+}t^{+} + v_{cs}{}^{-}t^{-}}{t^{+} + t^{-}}$$

# Use Flywheel for Frequency Stabilization

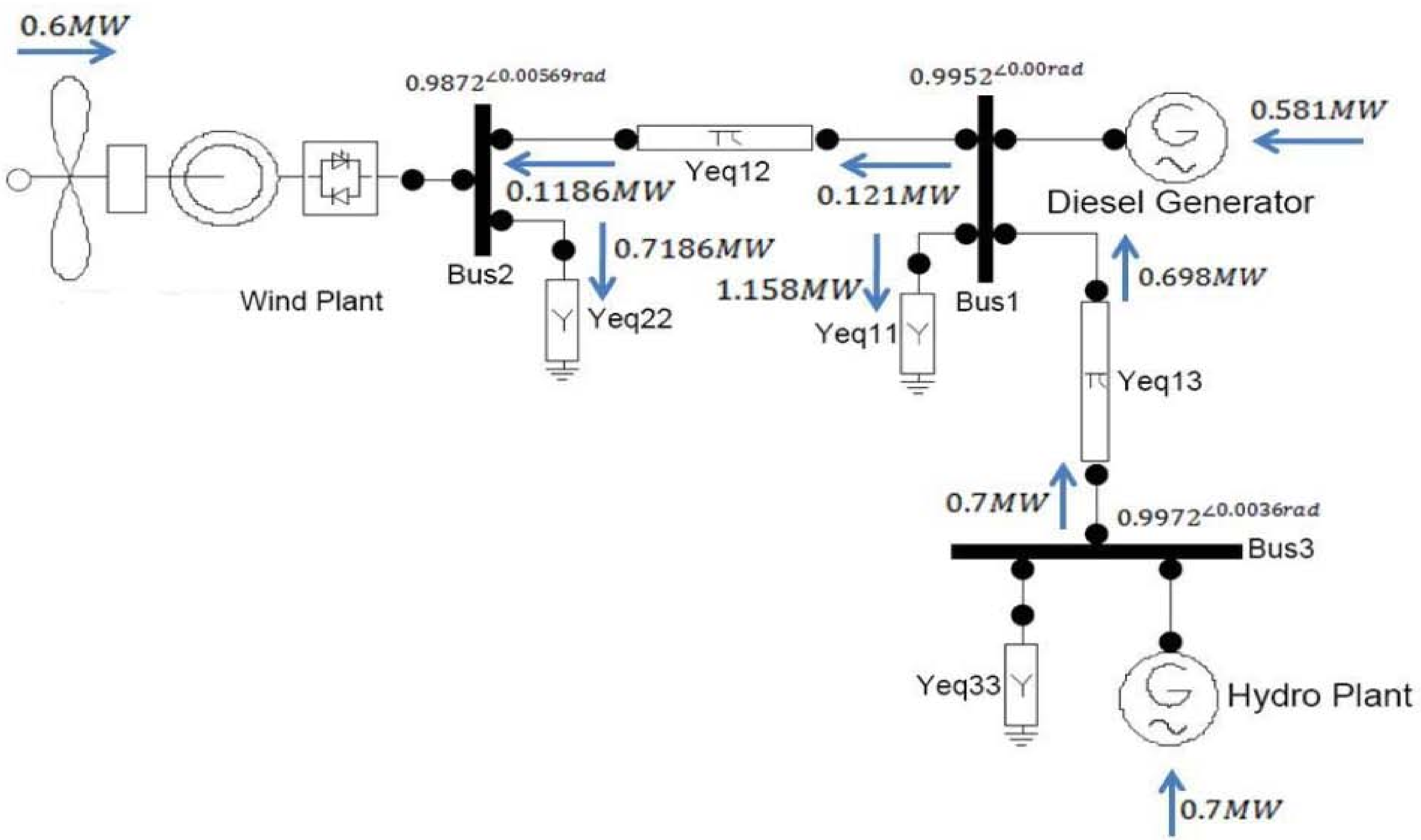
- Include dynamics of the entire system
- Set $i_{qs}^{*}$=0A in order to stabilize the disturbance



# Issues with small signal stability [9-11]

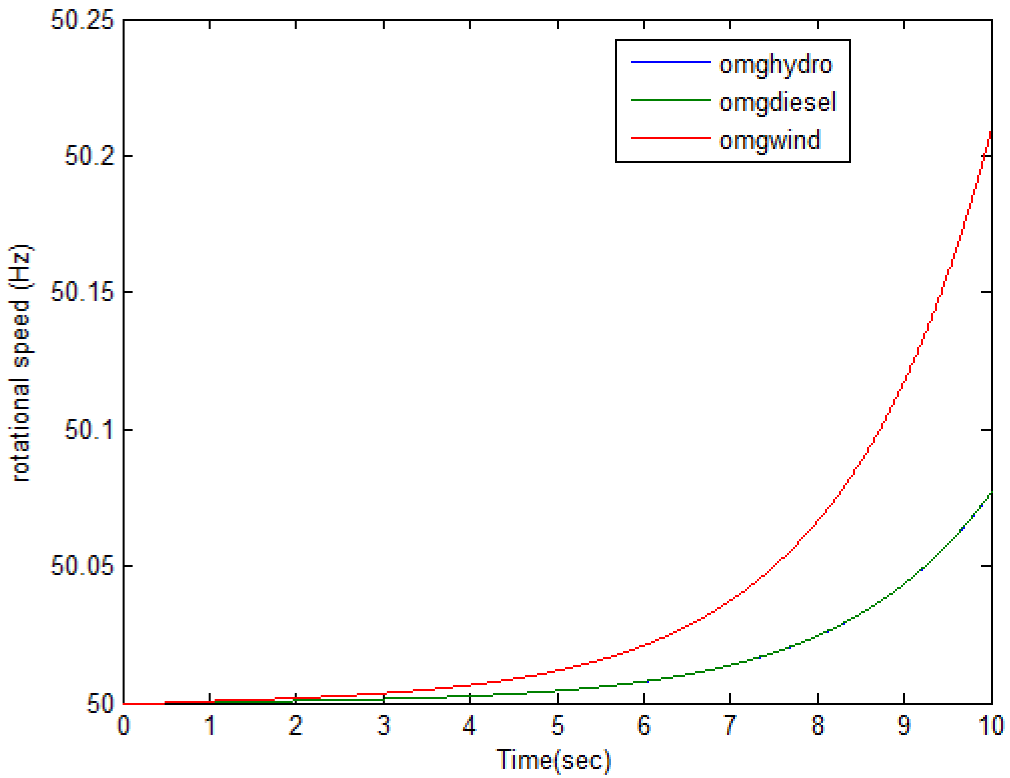
- Today's approach is to tune individual primary controllers (governors, DFIG of wind power plants, excitation systems) so that they are stand-alone stable for the assumed ``worst-case" system condition.
- All controllers are constant gain decentralized PID controllers responding to the local output variables (voltage magnitude, frequency).
- No reliance on communications.
- Small signal stability analysis run for the closed-loop system dynamics to ensure that linearized system dynamics are stable.
- Missed opportunity to design PMU-based primary control for ensuring small signal stabilization (with minimal communications).

# Flores island system



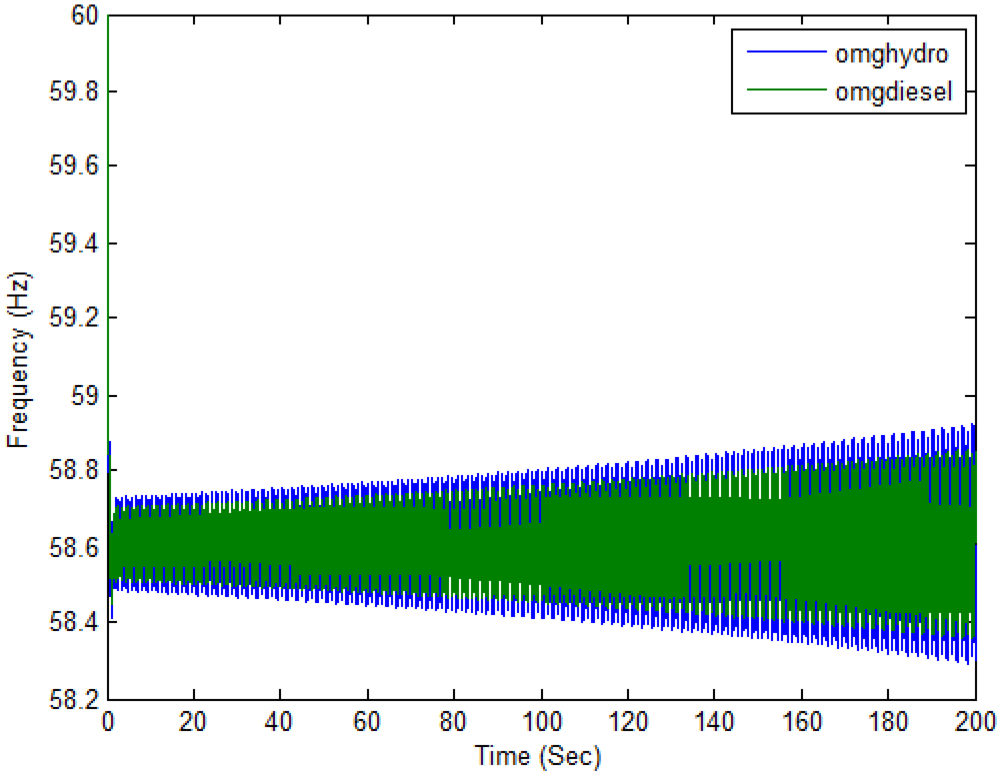
# Critical role of primary control

- Unstable Flores System without Governor and Excitation Control



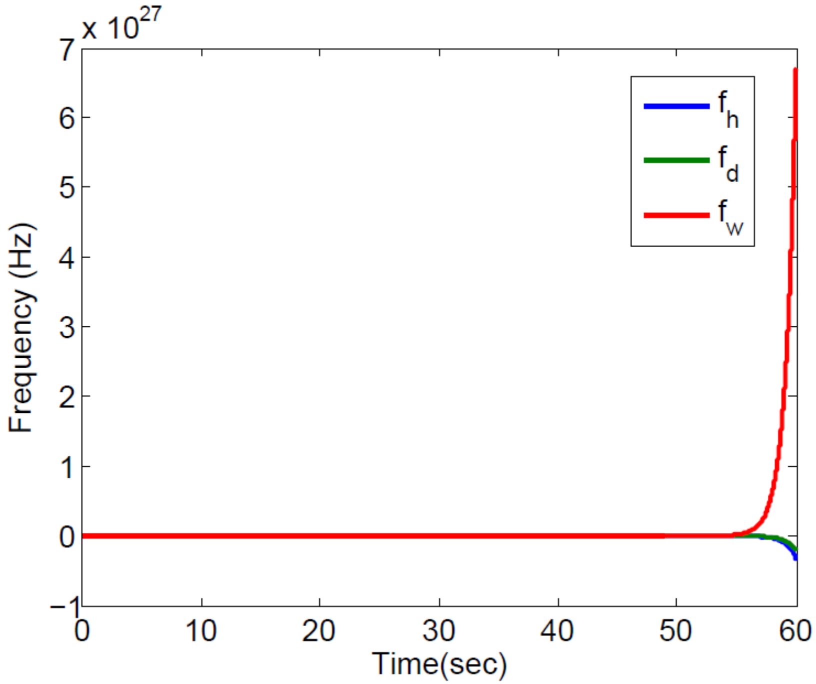
# Issue with stability with strictly decentralized control

- Unstable system with decentralized control

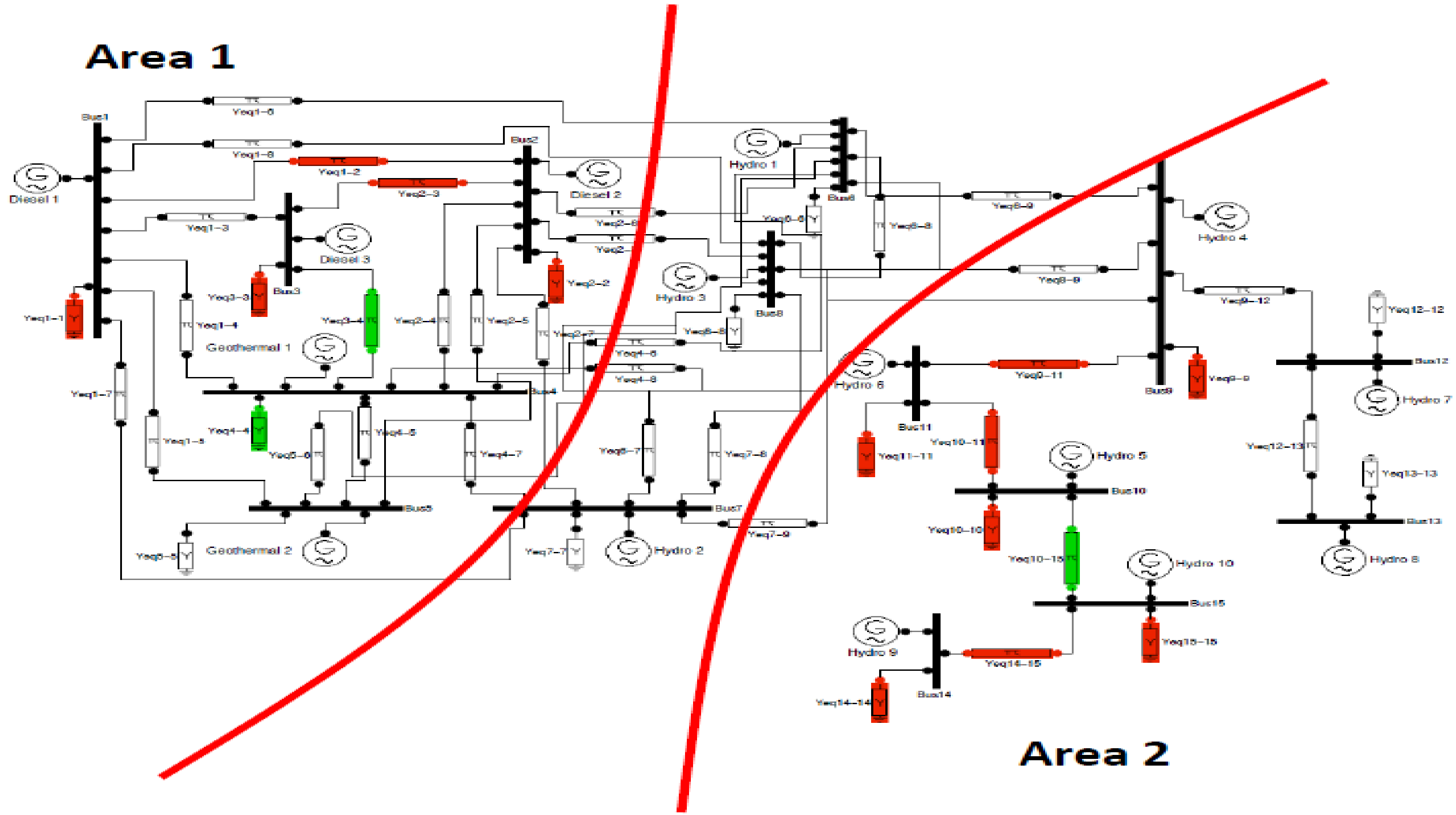


# Critical role of excitation control

- Weak connection, unstable system due to insufficient reactive power support



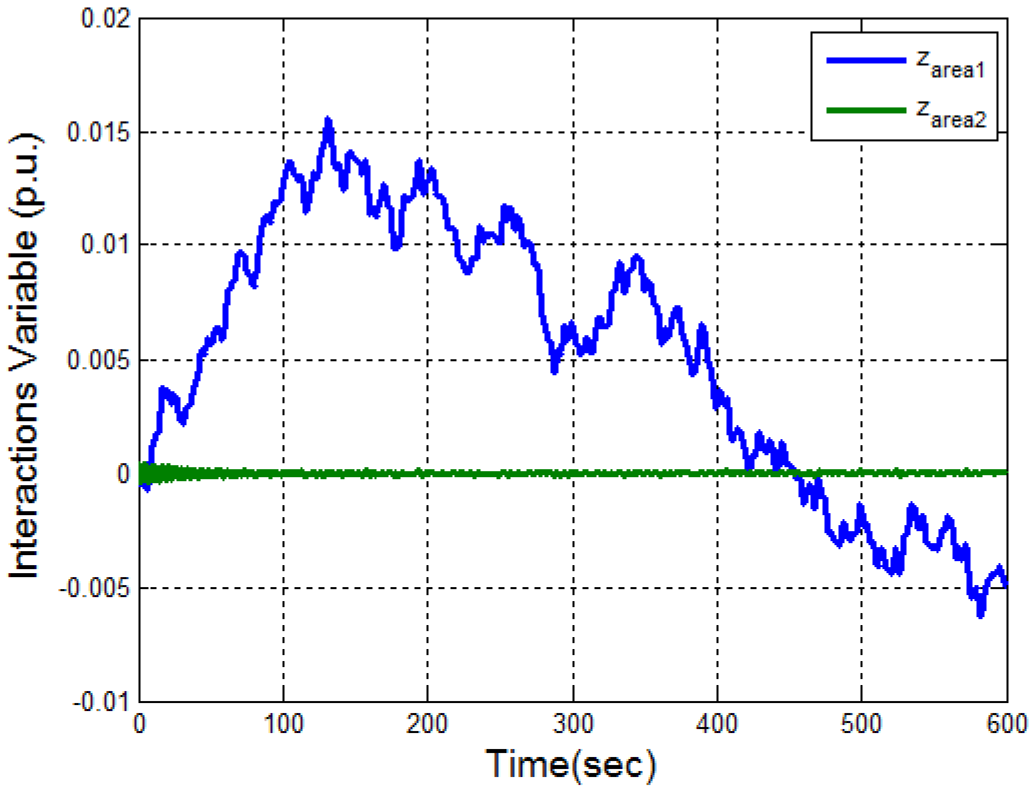
# Dynamics of interaction variables—Sao Miguel System



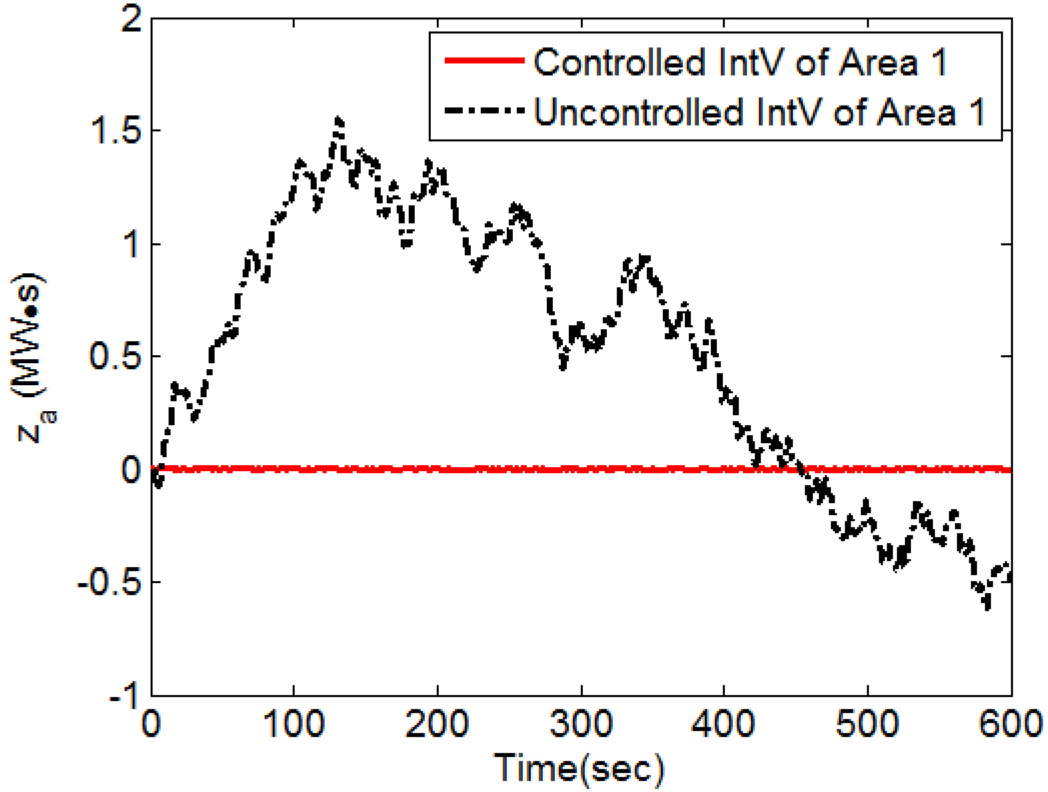

[2] M. Ilic "The Tale of Two Green Islands in the Azores Archipelago," Chapter 2 of Engineering IT-Enabled Sustainable Electricity Services : The Tale of Two Low-Cost Green Azores Islands.

# Key notion of interaction variable dynamics and their control

- Interactions variables of area-1 and area-2

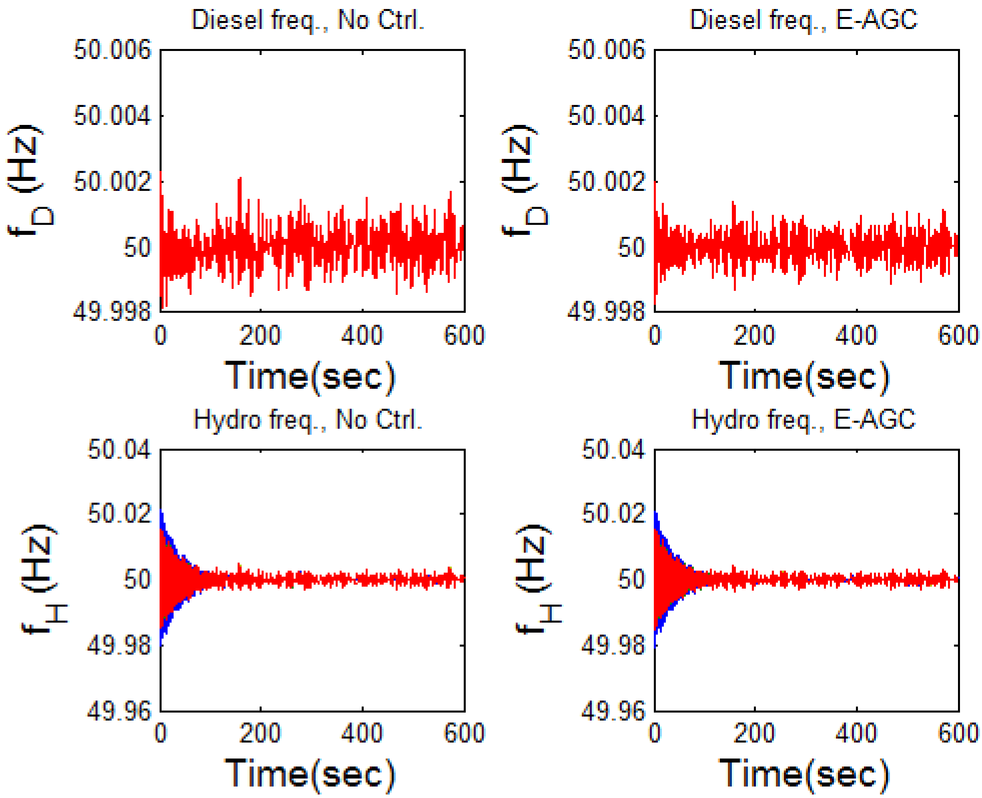


# ❖Controlled IntV v.s. uncontrolled IntV

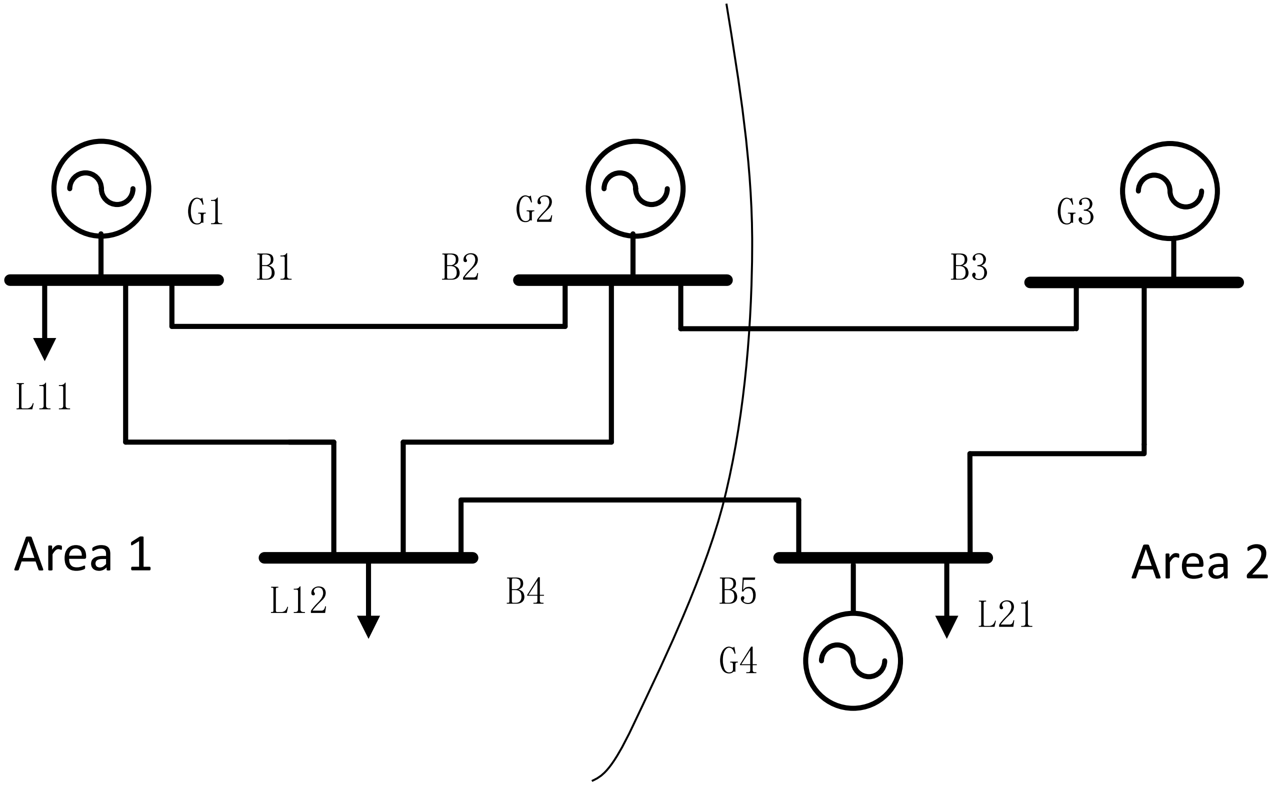


# Issues with intra-area dynamics

❖ Other states [still oscillations]



# No issues with QoS in today's industry—well-understood standards [15]




G1 and G2: Hydro Generators; droop1 = 0.03, droop2 = 0.025
G3 and G4: Combustion-turbine Generators; droop3 = 0.05, droop4 = 0.06

# Key assumptions of AGC

- Steady-state assumption
- Uniform frequency across the system
- Frequency biases are tuned so that

$$\beta_i = \sum_{k=1}^{N_i} \frac{1}{\sigma_k} = \sum_{k=1}^{N_i} \frac{Kt_k}{r_k} + \sum_{k=1}^{N_i} D_k$$

β: frequency bias
σ: speed droop
D: damping
Kt: control gain of the speed-governor
r : parameters of the speed-governor

# Issues with QoS in the changing industry [9-11]

- Technology-dependent droop characteristics
- Frequency deviations harder to differentiate than power (or angles) –NEED TO THINK MUCH MORE ABOUT THE IMPLICATIONS OF THIS!
- Back to continuous carefully designed reduced order models which can be used to systematically design an LQR for meeting pre-specified performance metrics (cost vs quality of regulation)

# Given technology, comparison of regular and advanced AGC (LQR) –a sample

## Case 1: Zero Mean Wind Disturbances (Good Wind Prediction)

Wind in this case is operating at its full capacity (Pw = 0.6 MW) and the prediction can be accurate.

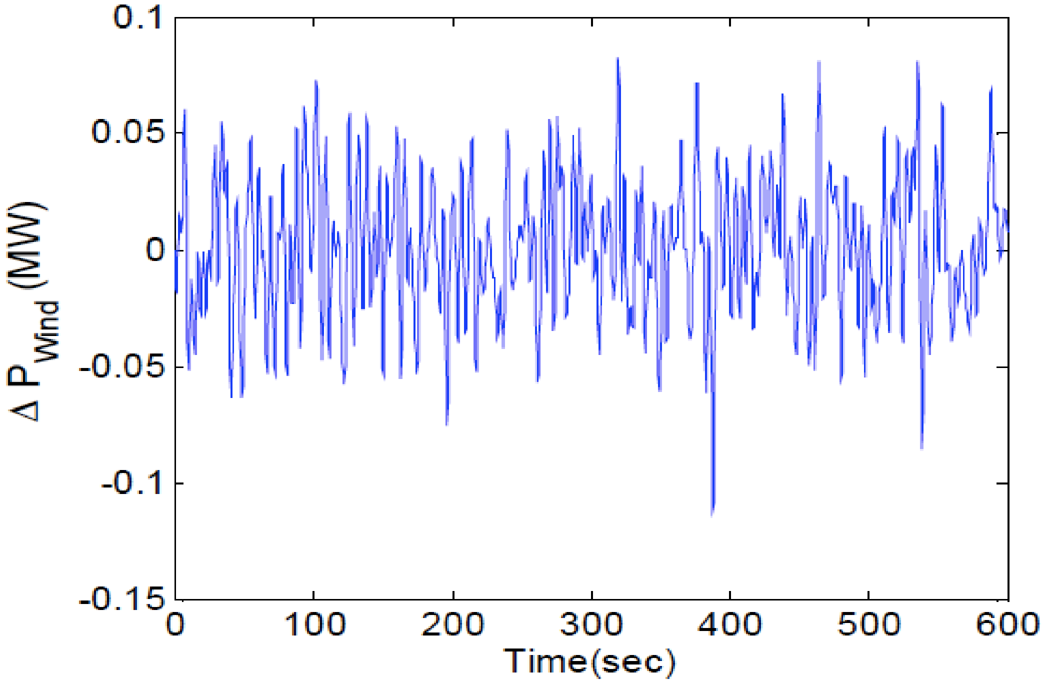
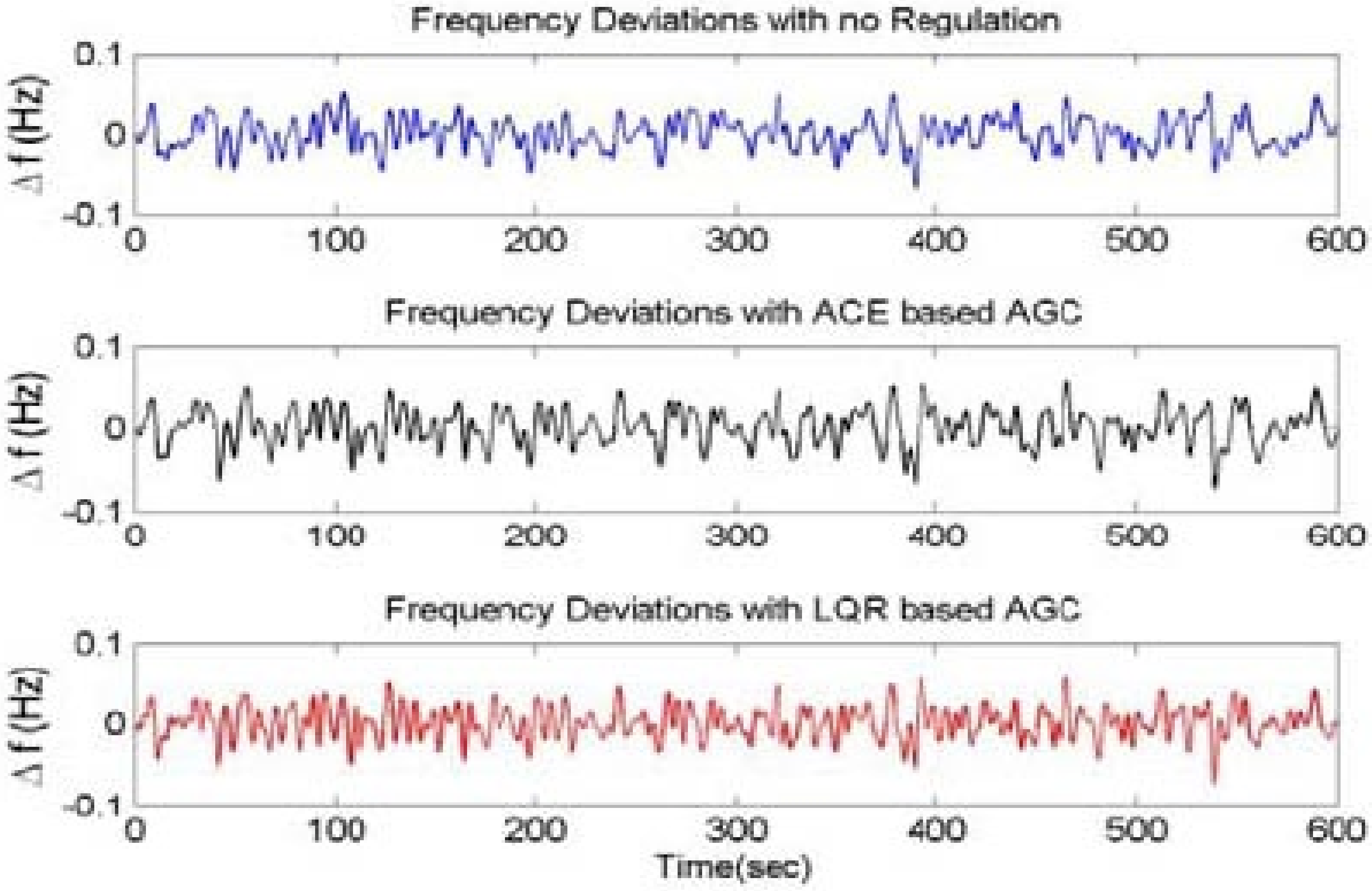
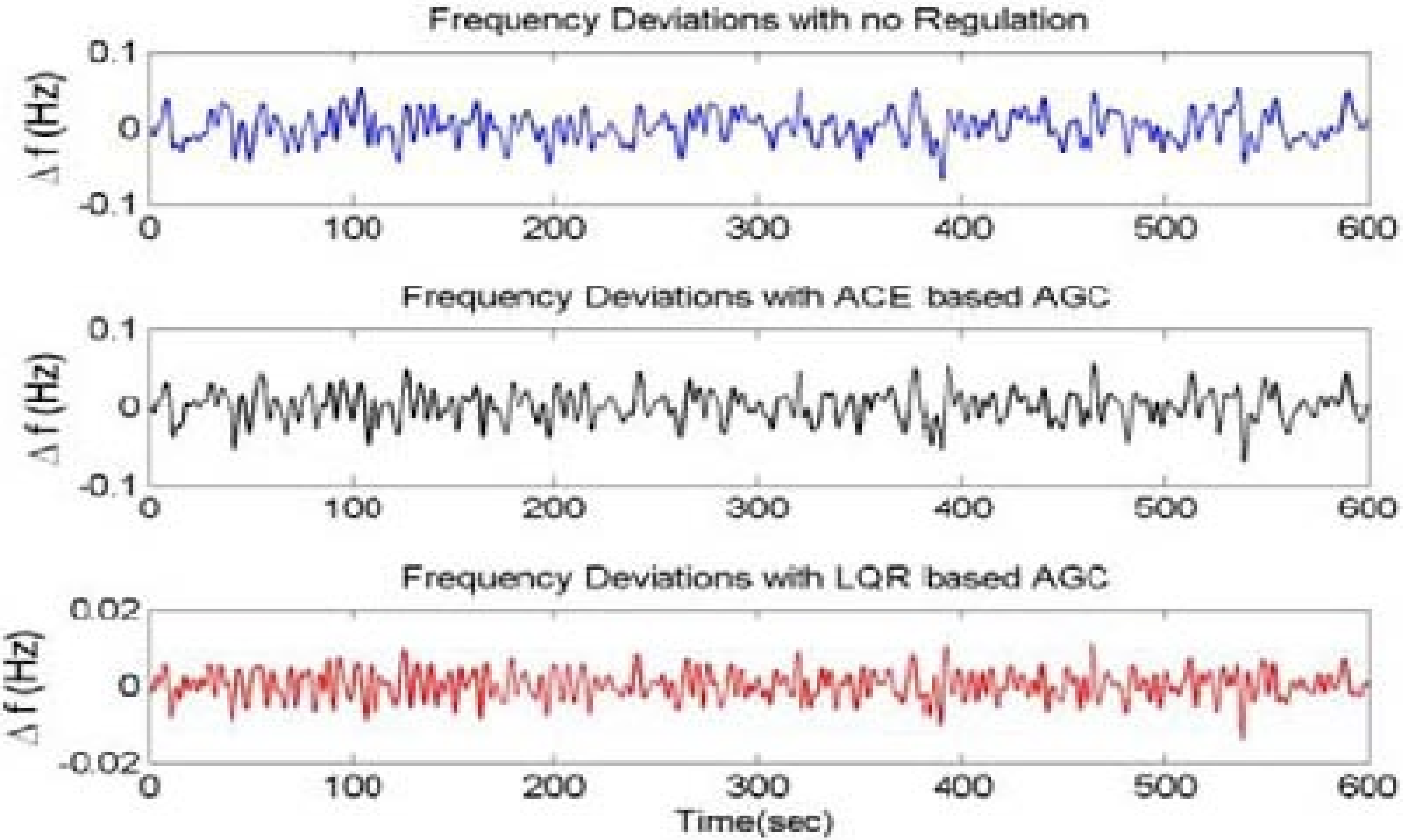


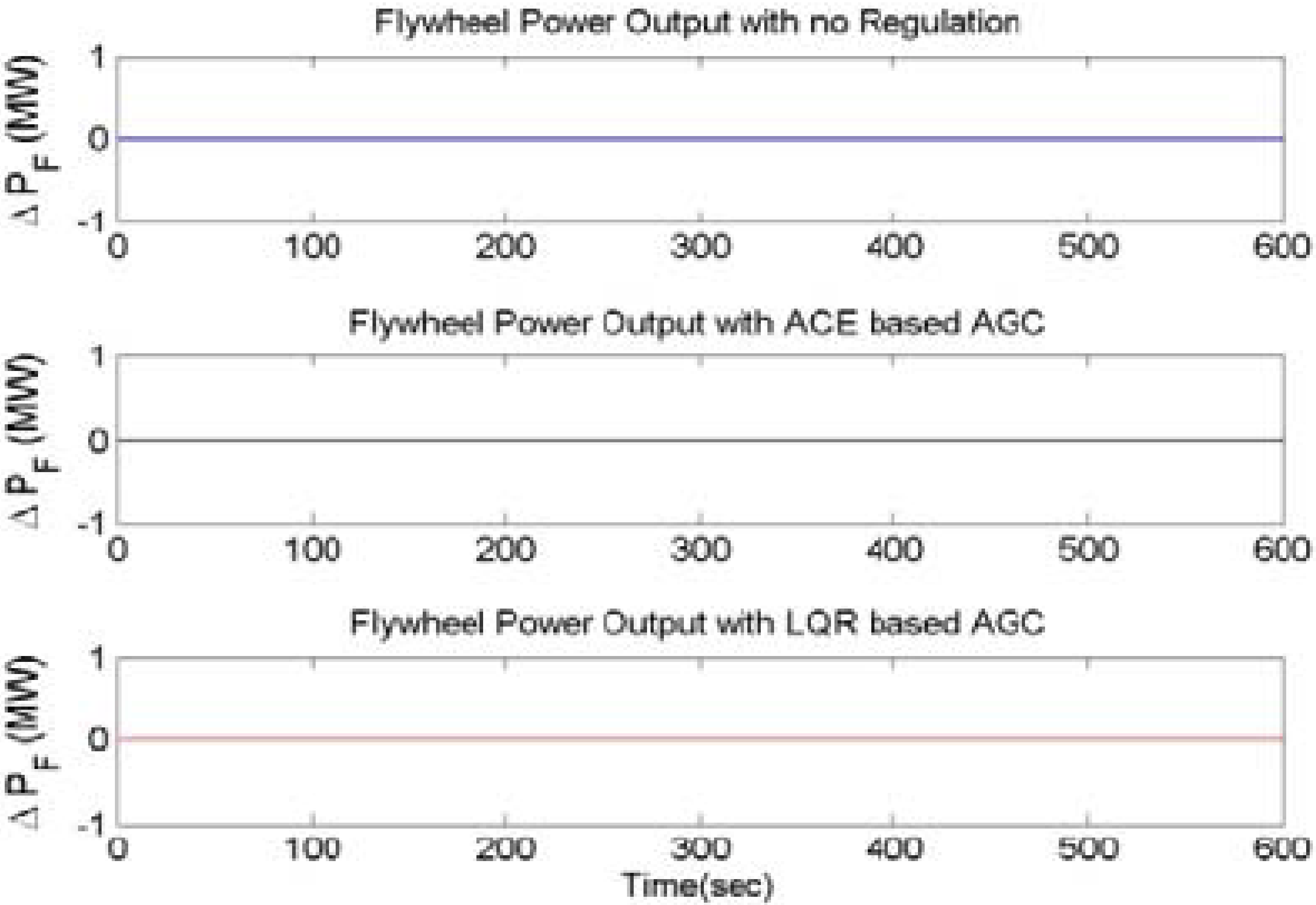

**Figure 1.1 Zero Mean Wind Disturbances and 5% Standard Deviation around the Operating Point in 10 minutes.**



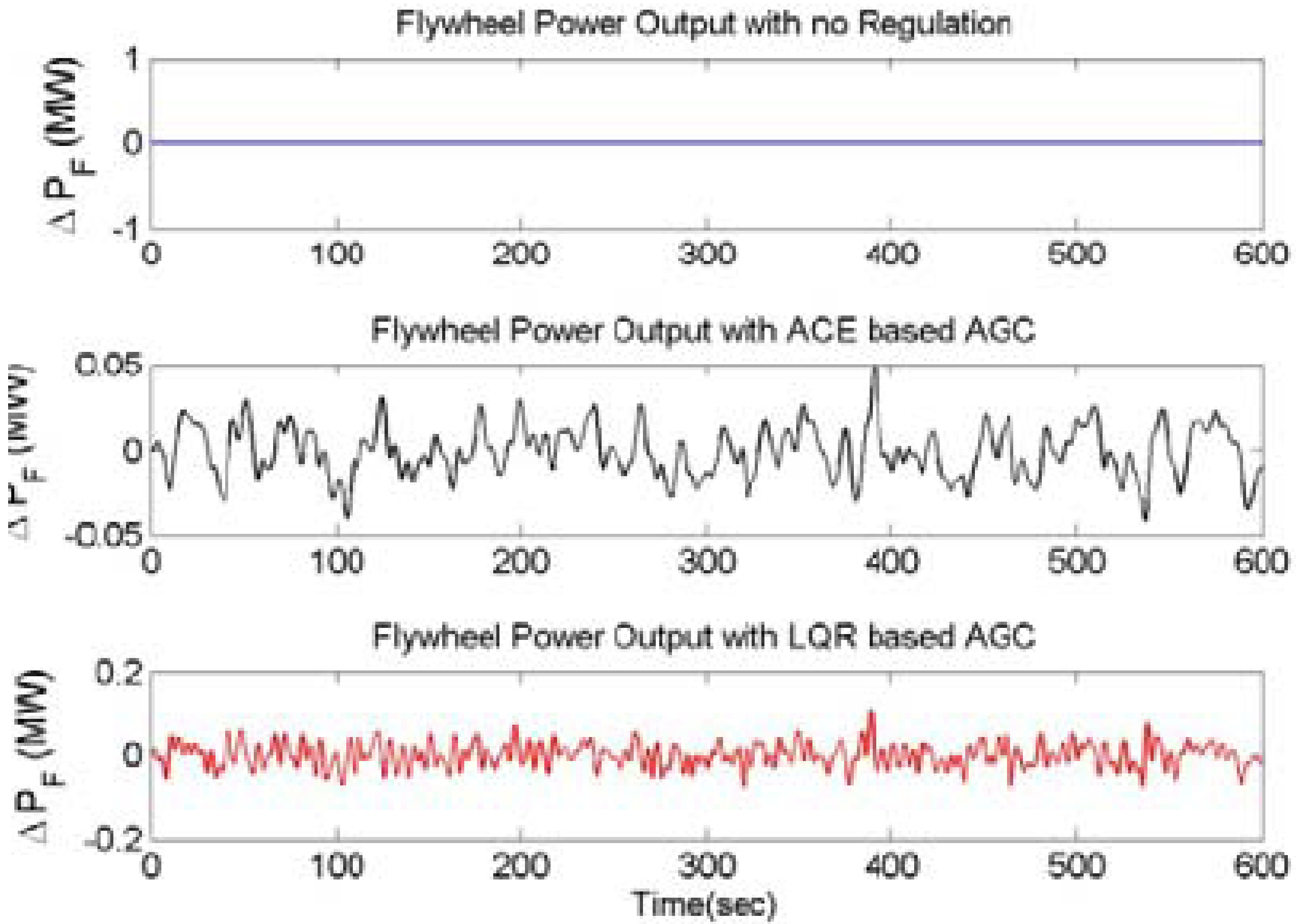

(a) AGC with Hydro Only



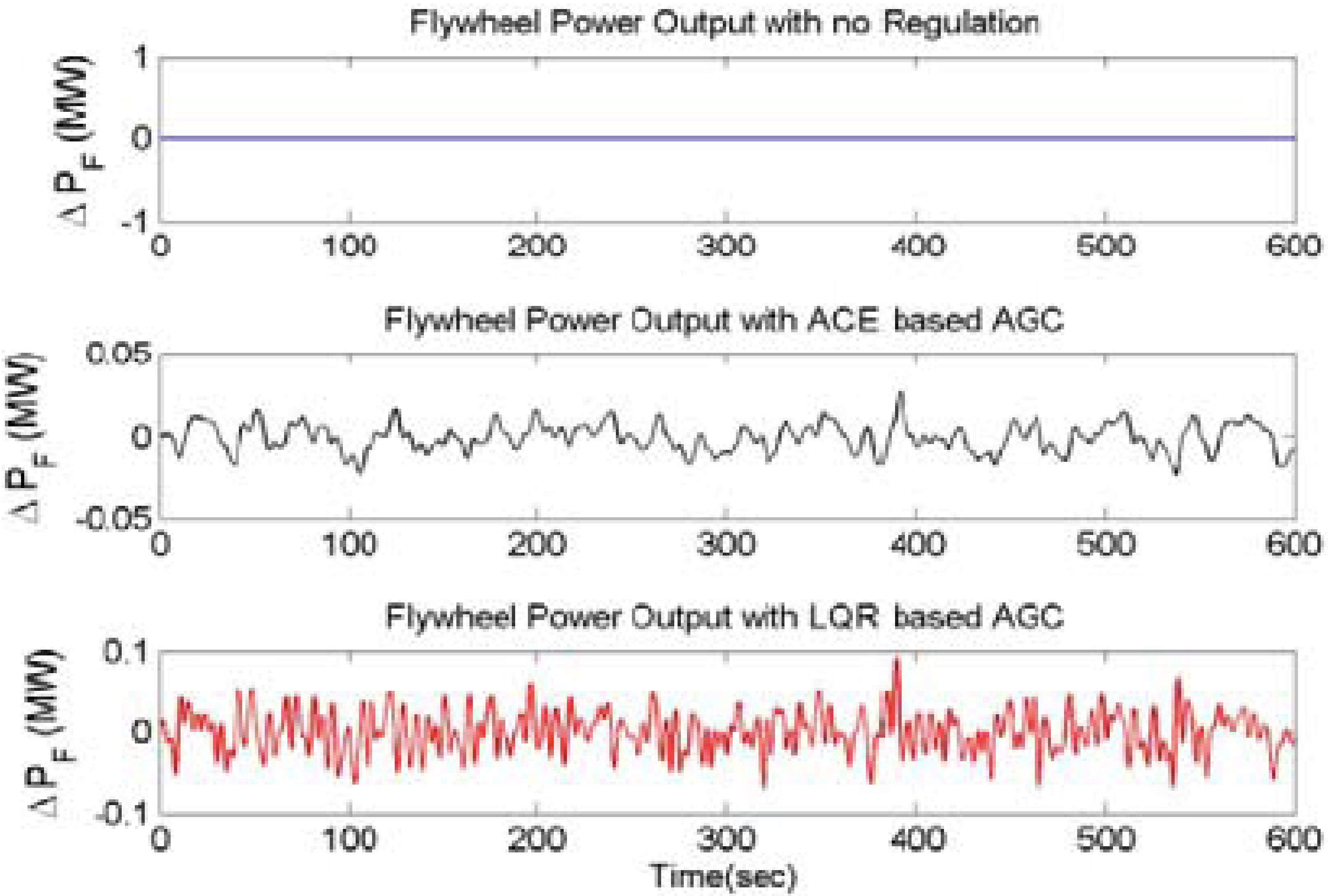

# (d) AGC with Diesel and Flywheel




# (a) AGC with Hydro Only



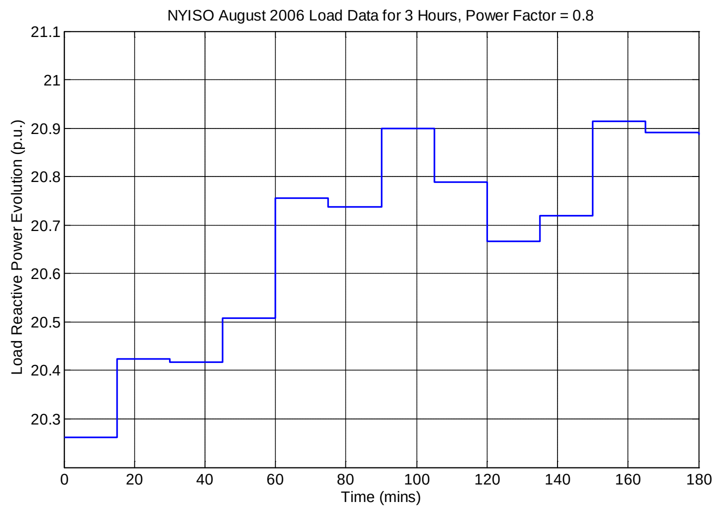

# (c) AGC with Flywheel Only

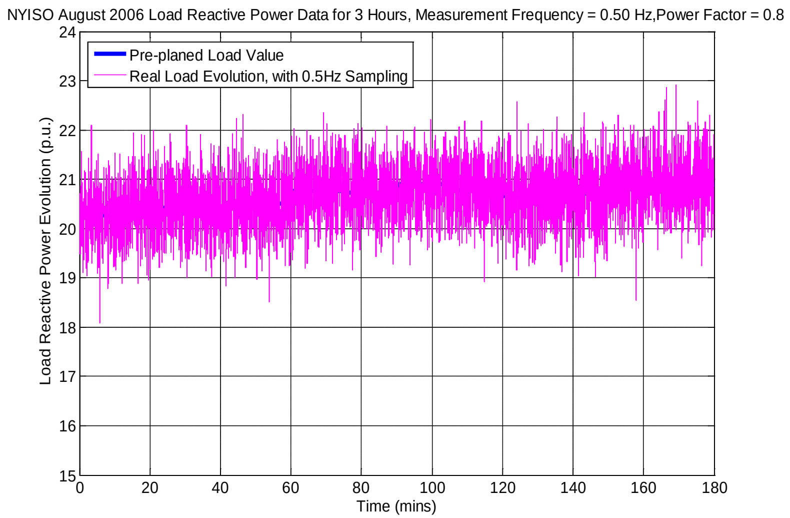



# (d) AGC with Diesel and Flywheel

# Issues with QoS for voltage

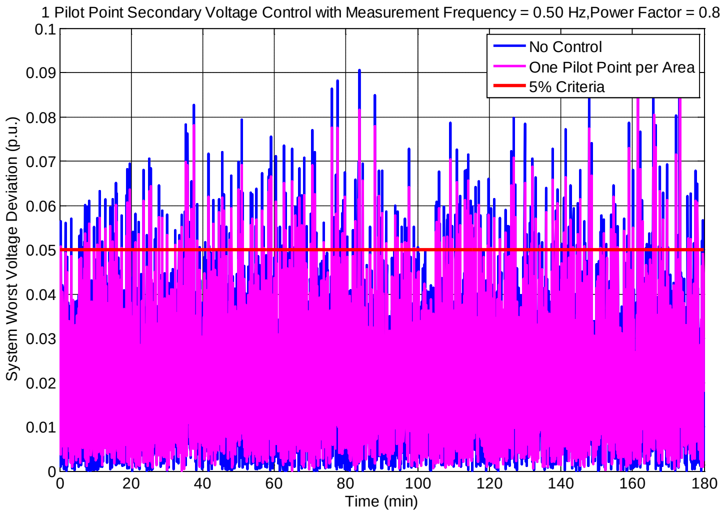
Scheduled load value and the disturbance around the value

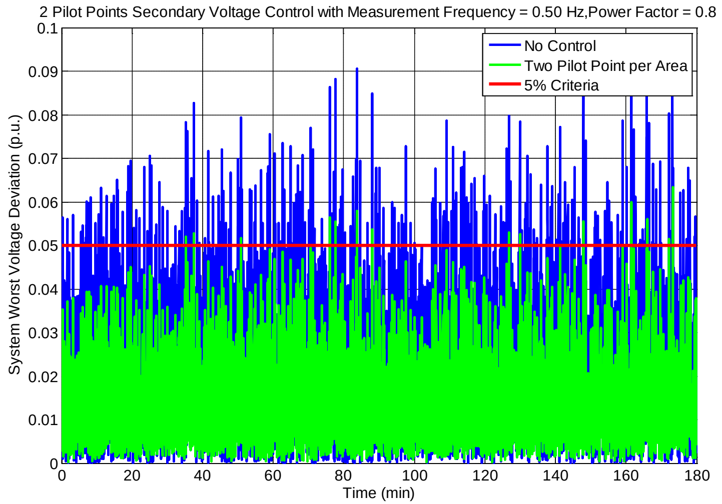


# AVC for the NPCC with PMUs

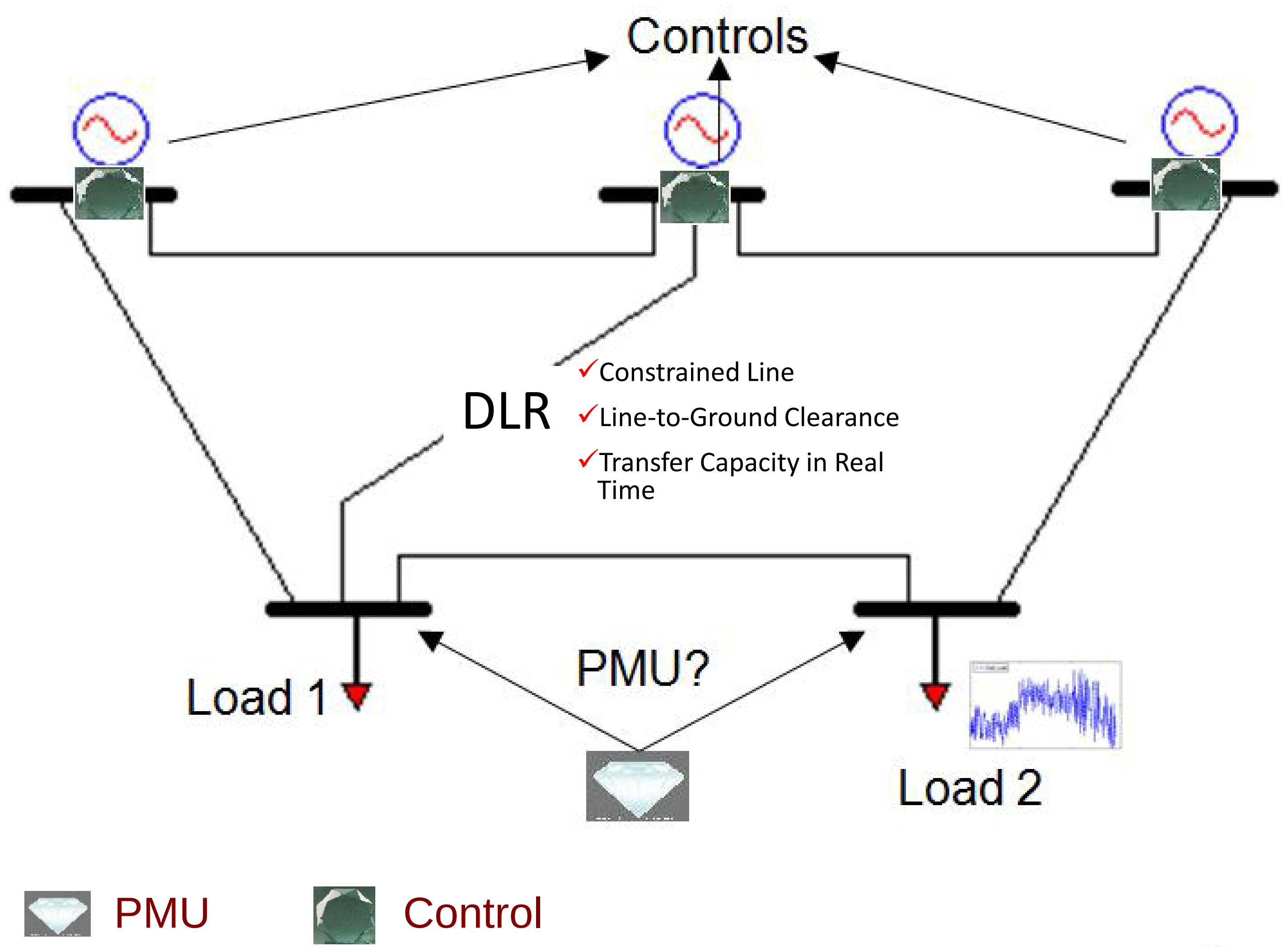
Simulations to show the worst voltage deviations in response to the reactive power load fluctuations (3 hours)



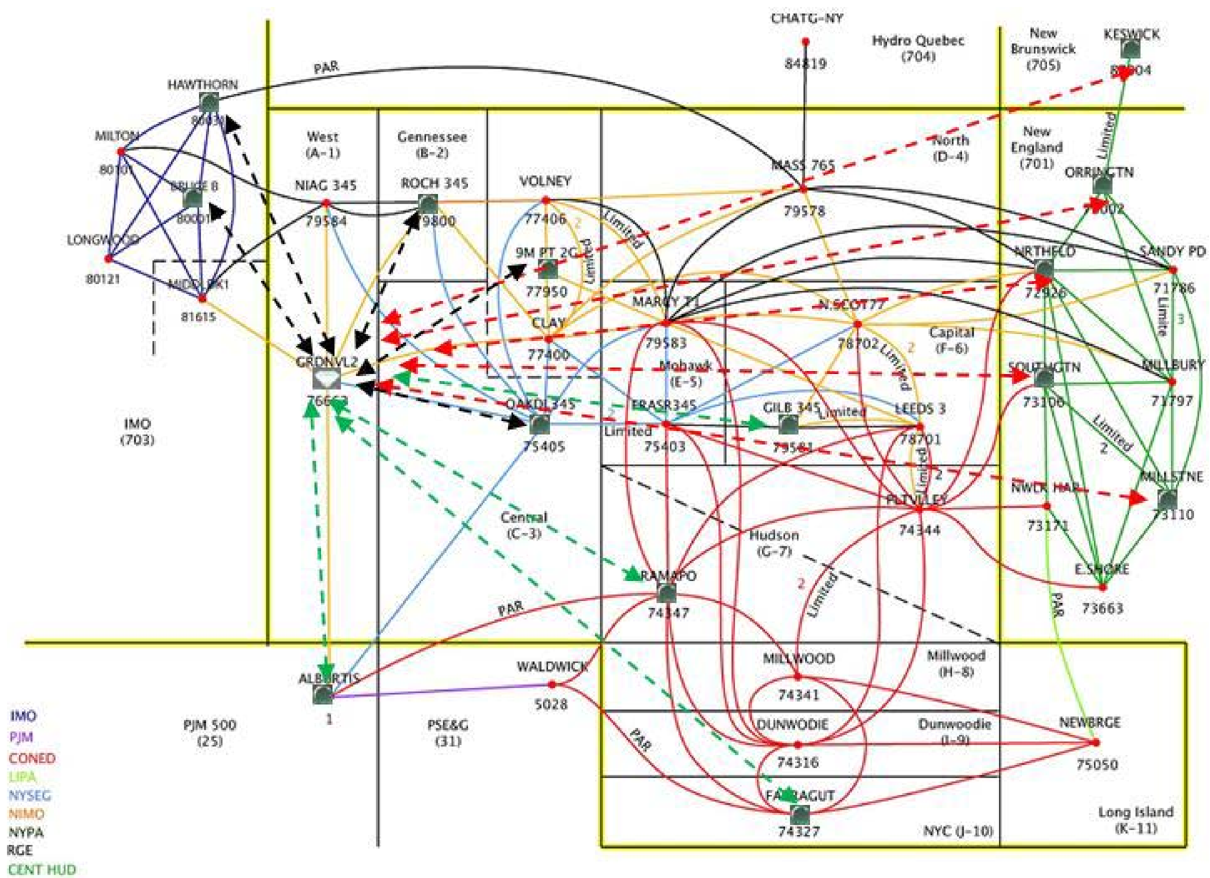

*2 Pilot Points Control Performs Better Than 1 Pilot Point!*

# Use of on-line fast and accurate measurements—Future [12]



# Northeastern Power Coordinating Council (NPCC) System

- Take NPCC system as *ONE AREA*; then put 1, 2 and 3 PMUs at pilot buses [13]



# Implications on standards for dynamics?

- The line between standards for safety, ensuring QoS and for avoiding stability problems not well defined.
- The more advanced decentralized control, the less need for fast communications.
- An important observation for possible path ahead: Effective decentralized control for preventing SSR and for preventing low-frequency inter-area oscillations have one common feature: They require lots of effort to cancel interactions with the rest of the system.

# Standardization efforts for smart grids

- Smart grids are targeted to enabling alignment of temporal and spatial characteristics of resources and users by means of a man-made electric power grid and its IT
- Critical to have standardized characterization of system components;
- Common Information Model (CIM) –primarily for steady-state characteristics of system components; major effort
- Recent efforts for establishing CIM for dynamic characterization of components; work in progress.

# "Smart Grid" ←→ electric power grid and IT for sustainable energy SES [14]

| Energy SES | Man-made Grid | Man-made IT |
|---|---|---|
| • Resource system (RS)<br>• Generation (RUs)<br>• Electric Energy Users (Us) | • Physical network connecting energy generation and consumers<br>• Needed to implement interactions | • Sensors<br>• Communications<br>• Operations<br>• Decisions and control<br>• Protection |

# Model-based IT for Smart Grids

- Dynamic models to monitor, communicate and control dynamic interactions within a smart system so that resources, users' preferences and governance are aligned temporally and spatially as much as possible.
- One could view the role of standards for dynamics as the basic means of defining what needs to be sensed, communicated and controlled so that desired closed-loop dynamics is achieved.
- Standards need to be defined at the component level, control area level and at the interconnection levels.
- Non-unique ways of achieving system-level dynamic performance.

# Possible approaches to standards for dynamics

- Essential for avoiding  emerging behavior in future electric energy systems
- Major questions concerning  limits on control and  type of control and communications required.
- Enhanced sensing, communications and control will reduce the need for stand-by (real power) generation reserve.
- Each (group of) components  must be responsible for safe and stable interactions with the  neighboring control areas at the pre-specified QoS –smart balancing authorities (SBAs); this is a direct generalization of control areas.

# Three qualitatively different paradigms for standardization of dynamics in future smart grids

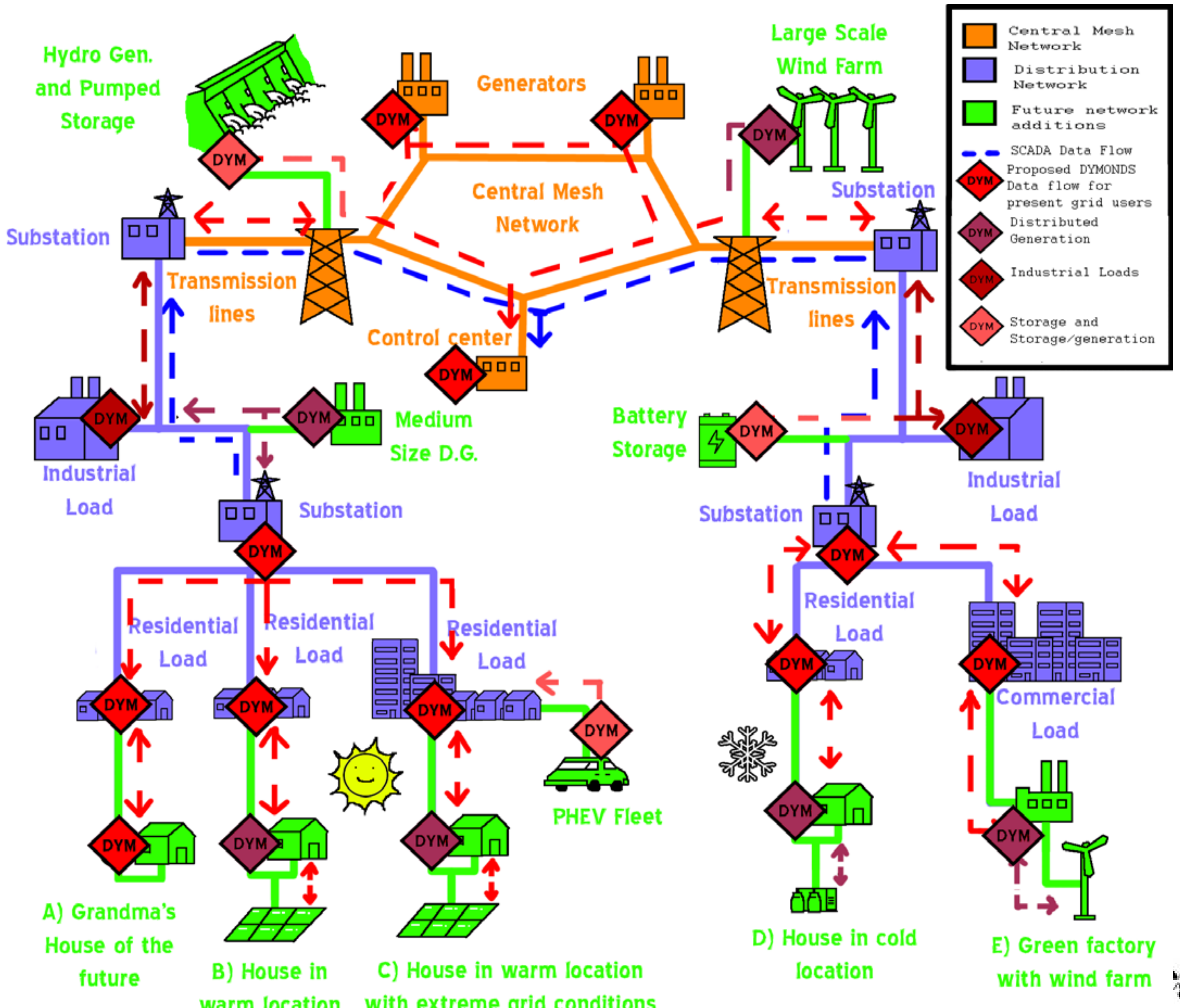
- **Plug-and-play standards for dynamics**, with no requirements for on-line communications. Much stricter standards at the component level will be needed for this to work.
- **System-level technical standards** based on minimal coordination of decentralized component-level standards.
- **Interactive protocols** for ensuring technical performance according to choice and at value)—dynamic monitoring and decision systems (DYMONDS).

# Major differences

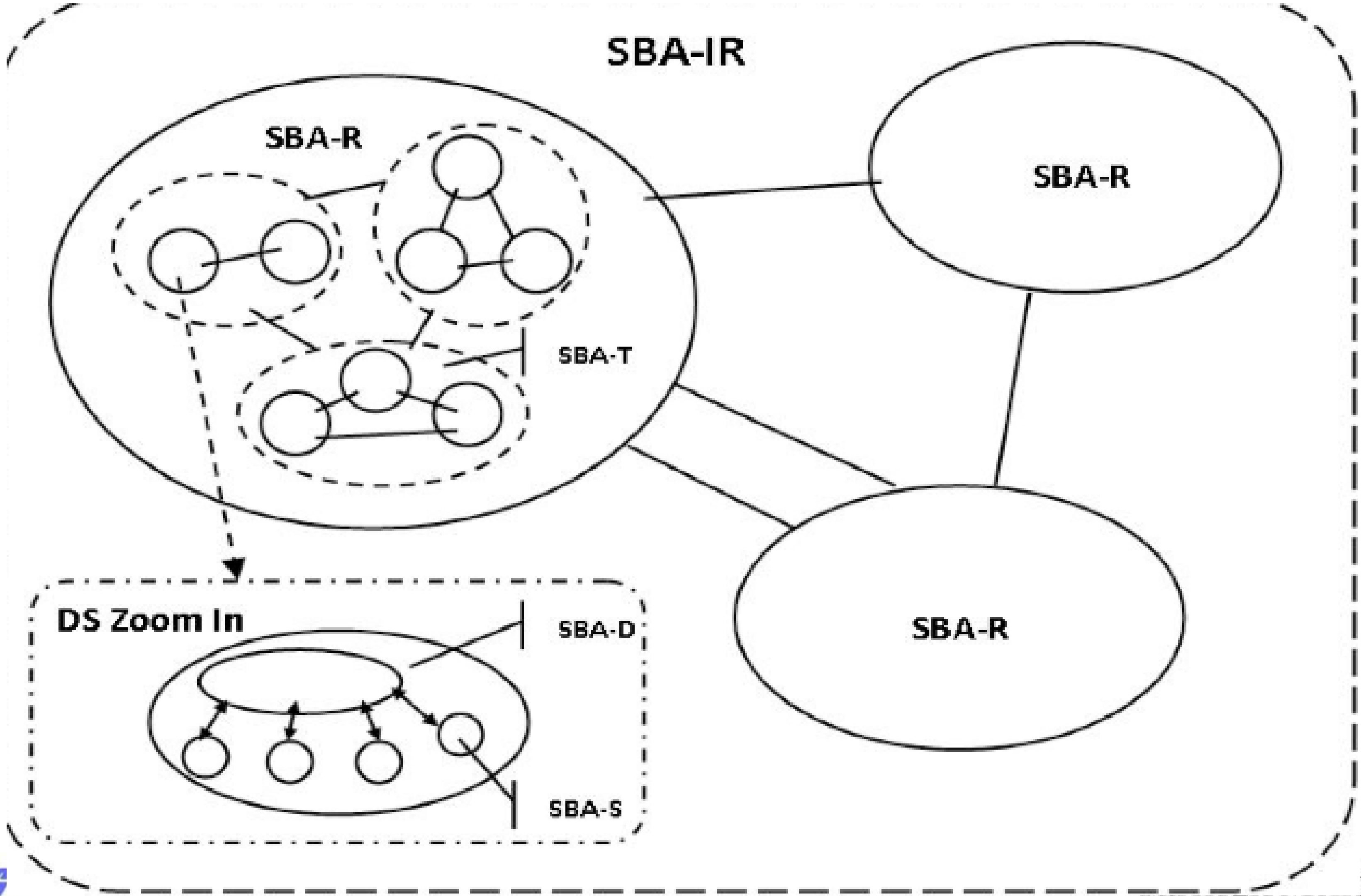
- Plug-and-play standards for dynamics –enhanced decentralized control for internalizing effects of interactions and canceling them. Lots of advanced local control.
- Standards based on minimal coordinated control of interaction variables for given nested architecture of future electric energy systems. Technical specifications at the decentralized level, economic and technical specifications at the system level. **Minimal exchange of technical signals.**
- Interactive protocols in terms of interaction variables evolving dynamically over time and space according to system users' preferences. Both economic and technical specifications at all levels. **Minimal exchange of technical and economic signals.**

- **STRUCTURE-BASED AND PROVABLE DYNAMIC PERFORMANCE.**

# DYMONDS-enabled Physical Grid [14]



# Multi-layered smart balancing authorities [14]



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